An Empirical Validation of the House Energy Rating Software AccuRate for Residential Buildings in Cool Temperate Climates of Australia

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Signed Statement

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Abstract

In 2003, the Building Code of Australia (BCA) introduced its first thermal performance requirements for residential buildings as a means to reduce Australia's energy consumption and greenhouse gas emissions in the construction sector. This mandated a minimum energy performance rating of 4 stars for all new residential buildings. This requirement was increased to 5 stars in 2006 and to 6 stars in 2010. The introduction of the 4-star requirement had only a minor impact on construction practices and construction costs. However, the adjustment to 5 and 6-star ratings resulted in changes within the building industry, particularly on timber floor construction. The BCA's requirements for increased star ratings and energy efficiency resulted in concerns within the building industry, one of which was in relation to the accuracy of the House Energy Rating scheme's (HER) software "AccuRate" and its capability to model the building envelope and provide the star rating. AccuRate was developed gradually over a number of years by the CSIRO and was primarily used by building designers as a design tool. When the energy efficiency section was incorporated into the BCA as part of the building approval requirements, AccuRate was developed into a regulatory tool. Consequently, industry and government have recognized the need to validate this software empirically.

The University of Tasmania, in collaboration with Forest and Wood Products Australia, the Australian Government, and housing developer Wilson Homes, constructed three test houses in Kingston, Hobart for the purpose of validating AccuRate empirically for the cool temperate climate zones of Australia. The test houses were built to standard building practices, comprising: brick veneer walls, aluminum-framed windows and Colorbond steel roofing. Two houses have suspended timber floors and the third house has a concrete slab floor.

An extensive array of instruments and data loggers was installed to measure and document the thermal performance of the three houses. Comprehensive AccuRate simulations of the test houses were carried out, and hourly measured and simulated data were compared. The research presents the findings of the graphical and statistical analysis of the variation between the simulated and measured data from the three test houses.

The findings demonstrate that while simulated and measured temperatures had comparable profiles for most zones of the three houses, individual hourly simulated temperatures did not in most cases, match the measured temperatures, and were at times quite dissimilar.

Simulated temperature ranges were larger in all zones of the houses than measured values. Simulated temperatures were closer to measured values in the slab floor house than in the two timber floor houses. In addition, simulated temperatures were closest to measured values in the living room and bedrooms of the concrete slab floor house and were furthest away from measured values in the hall way and roof space of all three houses and in the subfloor space of the timber floor houses. The large discrepancies between simulated and measured temperatures in these spaces of the houses require further investigation and resolution for the continuing improvement and calibration of the AccuRate software. The considerable disagreement of temperatures between simulated and measured values will significantly compromise the accuracy of the heating and cooling loads and consequently, the star rating of the software.

Acknowledgements

I wish to express my appreciation to a number of people who have contributed in a substantial way to the writing of this PhD thesis.

Firstly I wish to thank my supervisors, Professor Roger Fay, Dr. Florence Soriano, Associate Professor Gregory Nolan and Dr. Alan Henderson, for their friendly support, advice and guidance for the duration of this project. Particular thanks go to Florence who always encouraged me with the words “you can do it”; especially at times when I doubted my intellect, she offered me the option to ring her for advice at any time, even at 2 a.m. in the mornings (I never did). Roger always found some nice words of encouragement throughout this long research process. I thank Greg for establishing this research project and all the assistance he provided, especially during the installation of the measuring equipment at the test houses.

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I am indebted to my co-researchers; Philip McLeod, Sabrina Sequeira and Mark Dewsbury who always assisted me with so much that I had to learn during this project. Sabrina so often provided me with all the technical answers about computers, and Mark patiently helped me throughout the project.

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- Clark Liu who helped with the creation of the ‘on site’ climate data file;
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I could not have done this project without my wife Joanne who patiently waited for me for so long to complete this project and always provided encouragement, and financial support.

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List of Acronyms

BCA	Building Code of Australia
ASBEC	Australian Sustainable Built Environment Centre
FWPA	Forest & Wood Products of Australia
IPPC	International Panel on Climate Change
ABCB	Australian Building Codes Board
NAFI	National Association of Forest Industries
EEWG	Energy Efficient Working Group
IEA	International Energy Agency
HERS	House Energy Rating Scheme
EPBD	Energy Performance of Buildings
EEM	Energy Efficient Mortgages
FWPRDC	Forest & Wood Products Research & Development Corporation
WMO	World Meteorological Organization
UNEP	United Nation Environmental Program
CSAW	Centre for Sustainable Architecture with Wood
IPCC	International Panel on Climate Change
UNFCCC	United Nations Framework Convention on Climate Change
UNCED	United Nations Conference on Environmental Development
AGO	Australian Greenhouse Office
NatHERS	National House Energy Rating Scheme
EEWG	Energy Efficiency Working Group
DEWHA	Department of Environment Water Heritages and Arts
MEC	Model Energy Code
BREDEM	Building Research Establishment Domestic Energy Model
SAP	Standard Assessment Procedure
GMI	Glass Mass and Insulation Council of Australia
TMY	Typical Meteorological Year
IEA	International Energy Agency
BERS	Building Energy Rating Scheme
NABERS	National Australian Built Environment Rating Scheme
BASIX	Building Sustainable Index
HVAC	Heating Ventilation and Air Conditioning
SERI	Solar Energy Research Institute
PASSYS	Passive Solar System
NIST	National Institute of Standards and Technology
BESTEST	Building Energy Simulation Test

Chapter 1: Introduction

As early as 1950, Revelle observed that World War II, economic expansion, global population growth and fast growing energy consumption were likely to produce a dangerous increase in the amount of carbon dioxide (CO_2) in the earth's atmosphere (Gore 2006). In 1957, air samples at the research station at the top of Mouna Loa in Hawaii, USA showed a rise in CO_2 levels in the atmosphere (Revelle & Suess 1957). International awareness of global warming was growing and in 1988 the International Panel on Climate Change (IPCC) was formed, with the purpose of further evaluating knowledge on climate change.

One of the international concerns was that buildings consume one third of the world's resources (Atkinson 2006). In 2008, the Australian Sustainable Built Environment Council (ASBEC) reported that the building sector in Australia consumed about 19% of total energy, contributing a greenhouse gas emission of 23% of Australia's total. Residential buildings were found to be responsible for emitting about 13% of greenhouse gas emission (Australian Sustainable Built Environment Council 2008).

The Australian government examined the building sector's greenhouse gas emissions. They are detailed in the National Greenhouse Strategy document (Australian Greenhouse Office 1998a), which recommended that all commercial and residential buildings should adhere to energy efficiency standards based on thermal performance ratings. In 2003 the Building Code of Australia (BCA) introduced the first thermal performance requirements for residential buildings and mandated a minimum 4-star performance rating. This was increased to 5-stars in 2006 and 6-stars in 2010.

The introduction of the 4-star rating had a minimal impact on construction requirements. However, the move from 4 to 5 and 6-star conditions had considerable impact, especially on residential buildings using a timber platform floor construction. Various industry groups raised serious concerns about the new energy efficiency requirements, especially the construction cost implications and the accuracy of the simulation program used to assign star ratings. (Forest & Wood Products of Australia 2008; National Association of Forest Industries 2006).
The framework for several thermal modelling programs was established by the National House Energy Rating Scheme (NatHERS). Three software programs were endorsed, namely:

- AccuRate;

- FirstRate;
- BERS.

Each one of these programs can be used to demonstrate building energy efficiency compliance with the BCA. The AccuRate thermal simulation software, which was developed by the CSIRO, is used as the benchmark for accrediting other House Energy Rating Software (HERS). One of the major concerns raised by the industry was the accuracy of the star-rating program. The Housing Industry Association reported that builders regard the star-rating software as costly,' green blinding' and inherently unreliable (Hedley 2010). It also suggested that energy efficiency requirements created a multi-billion dollar component of the building and construction industry and those inaccurate star-rating assessments might result in a considerable financial burden to Australian home owners.

Williamson et al. (2001) reported that during the NatHERS development, no testing of the scheme against reality was conducted, and further stated that the star-rating is meaningless, as there is no correlation between star-ratings and household energy consumption and greenhouse gas emissions.

Further criticism of the AccuRate software model was expressed by the National Association of Forest Industries (NAFI) in March 2006, which noted that AccuRate's simulation of energy loads might be flawed. NAFI further stated, 'Clearly the lack of validation of the computer modelling against the actual performance of current building materials and practices is of critical concern to the timber industries' (National Association of Forest Industries 2006).

One of NAFI's main contentions was that AccuRate was developed using a thermal mass philosophy, that buildings with internal thermal mass materials, such concrete slab floors, when assessed, automatically achieve a somewhat higher star-rating. Since a timber framed light-weight construction does not fit this philosophy, it is seemingly penalised by the star-rating system. However, Willrath, whose company Solar Logic developed the thermal assessment software BERS, responded that the star-rating simulation remains the most accurate way of modelling thermal performance and further, as computers become more powerful, the modelling will improve incrementally (Hedley 2010). Willrath also stated that as there might be uncertainty about the accuracy of the rating program, further financial support is needed for proper validation and further improvement of the software.

As a result of the concerns regarding the accuracy of the AccuRate software, the CSIRO, together with industry representatives and federal government agencies, agreed that the House Energy Rating Scheme (HERS) AccuRate should be validated empirically, comparing simulated values with measured values in a test building. The validation would then inform industry and government of the capability of AccuRate to predict room temperature, star-ratings and energy loads in buildings. An acceptable correspondence between simulated and measured values would provide industries with confidence in the program, while large variations between simulated and measured values would direct software developers to areas of the software requiring further improvements.

Consequently, the Five Star Thermal Performance project was initiated in 2005 by the Centre for Sustainable Architecture with Wood (CSAW) within the University of Tasmania's School of Architecture & Design, with funding from the Forest & Wood Products Research & Development Corporation (FWPRDC) and the Australian Greenhouse Office (AGO).

This research project aimed to validate empirically the performance of the House Energy Rating Software AccuRate, using industry-standard types of building construction. Initially, this project was known as the No Bills and Five Star House project; it involved the construction and monitoring of three test houses at Mornington, Hobart, Tasmania. The houses were designed by the Launceston home developer CG&M Design Pty.Ltd. and were to be:

- The No Bills House, with an 8.5-star rating, having no external service requirements;
- The Best Five Star Timber Floor House with an enclosed subfloor; and
- The Best Five Star Concrete Floor House with a concrete slab-on-ground floor construction.

For financial reasons the original concept did not proceed. However, the proposal was reformulated into the Five Star Thermal Performance project. In this new proposal, two sets of test buildings were designed and constructed: three light-weight timber-framed test cells in Launceston and three 2-bedroom light-weight timber framed houses in Hobart, Tasmania.

This thesis addresses the empirical validation of AccuRate through the evaluation of three 2-bedroom light-weight framed houses in Hobart. These houses consisted of several rooms with large windows and glazed sliding doors. Dewsbury's (2011) research addressed empirical validation by analysing the thermal performance of three light-weight timber framed test cells in Launceston, Australia. These test cells consisted of one room with no windows.

The aim of this research project is to validate empirically the AccuRate software by monitoring the thermal performance of three test houses in a cool temperate climate area of Australia.
While a similar project validated AccuRate empirically, using three light-weight timber framed test cells, this is the first empirical zone temperature validation of AccuRate using purpose-built light-weight timber framed houses.
Arising from the aim of the research project, the research question is: How well does the AccuRate software predict indoor room temperatures in houses located in the cool temperature climate zones of Australia?

The research project's hypothesis is: AccuRate's simulated temperatures will be similar to measured temperatures in the three test houses.
Specifically, the objective of this research project is to compare AccuRate's simulated hourly indoor temperatures with measured internal hourly temperatures for the three purposes-built houses in Kingston, Tasmania.

The key components of this research are presented as follows:
Chapter 2 discusses the history of climate change issues, Australia's greenhouse gas emissions and Australian's response to climate change. This chapter also focuses on the strategies for Australia's building industries to reduce their greenhouse gas emissions. Finally, this chapter summarises house energy rating schemes in developed countries and concludes with a detailed description of Australia's house energy rating schemes, in particularly the House Energy Rating Software, AccuRate.

Chapter 3 describes the methods used to validate simulation programs. This chapter examines empirical validation methods and establishes the important factors constituting a successful empirical validation project. A number of validation case studies of previously completed projects overseas and in Australia are briefly described.

Chapter 4 describes in greater detail the methods used for empirical validation in this research project. The chapter establishes the importance of measurement profiles and focuses on the numerous construction and weather input data for the simulations. This chapter concludes with a description of graphical comparisons of simulated and measured temperature data and the subsequent analysis of some recent completed projects.

Chapter 5 illustrates the design and construction of the three test houses in Kingston, Tasmania. The first part explains the star-rating process for each house while the second part provides a detailed presentation of the construction details of the houses.

Chapter 6 is presented in three parts:

- Part 1 focuses on the description of the thermal monitoring equipment and the positioning of the sensors within the houses.
- Part 2 provides a detailed illustration of the installation of sensors and cables inside the houses.
- Part 3 addresses the data management, including their storage, cleaning and checking.

Chapter 7 explains AccuRate's thermal performance simulation of the test houses. It covers the changes made to AccuRate's input data that were necessary to provide a more realistic representation of the construction details and actual on-site weather conditions. In addition, this chapter describes the changes made to input files to simulate the free-running operation that is, (no heating and/or cooling) of the houses, when the houses were not occupied. Finally, the chapter concludes with a detailed description of the preparation of site climate data for AccuRate simulation.

Chapter 8 is presented in three parts:

- Part 1 examines whether air or globe temperatures should be used for the validation of AccuRate.
- Part 2 presents the graphical comparison of simulated and measured temperatures. Measured and simulated temperature profiles and daily maximum and minimum temperatures are shown graphically for selected zones of the houses. Finally, temperature ranges and differences between simulated measured values are compared between the houses, as a means of examining temperature trends.
- Part 3 focuses on a more in-depth statistical analysis of the empirical validation data, and the differences between simulated and measured temperatures, particularly examining the residual values (the difference between measured and simulated temperatures) for each zone of the houses.

The conclusion and areas recommended for further research are discussed in Chapter 9.
The appendices include supporting documents, namely: indent of additional photographs of the installation of monitoring equipment in the test houses, specification of sensors and monitoring

equipment, and an additional set of graphical and statistical analyses prepared for this research project.

Chapter 2: Climate Change and the Construction Sector

This chapter presents an overview of the global problem of increased greenhouse gas emissions, anticipated climate changes and the global action to reduce greenhouse gas emissions. It focuses on Australia's response to greenhouse gas emission abatement strategies, particularly in the context of the building industry. In addition, this chapter reviews some of the House Energy Rating tools available and finally, provides a brief overview of the Australian House Energy Rating Tool "AccuRate".

2.1. History of the Climate Change Issue

In 1950, scientist Roger Revelle formed a hypothesis that World War II, economic expansion, explosive population growth and fast growing energy consumption were likely to produce a dangerous increase in the amount of carbon dioxide (CO_2) in the earth's atmosphere (Gore 2006). Revelle proposed and designed a scientific experiment to collect samples of CO_2 high in the Earth's atmosphere at numerous locations. In 1957, together with Charles Keeling, Revelle established the first research station at the top of Mauna Loa, a volcanic mountain at Hawaii, USA. This location in the middle of the Pacific Ocean was chosen so that test air samples would not be contaminated by industrial emissions. In 1958 Revelle and Keeling began launching weather balloons and analyzing the amount of CO_2 in the air samples they collected every day. After the first few years of taking air samples, the trend of rising CO_2 levels in the atmosphere had already become clear (Gore 2006).

Figure 2.1 indicates rising CO_2 concentration in the atmosphere (from 317ppm to 365ppm), measured at an altitude of about 4000 meters, on the top of Mauna Loa Mountain in Hawaii, from 1959 to 1998.

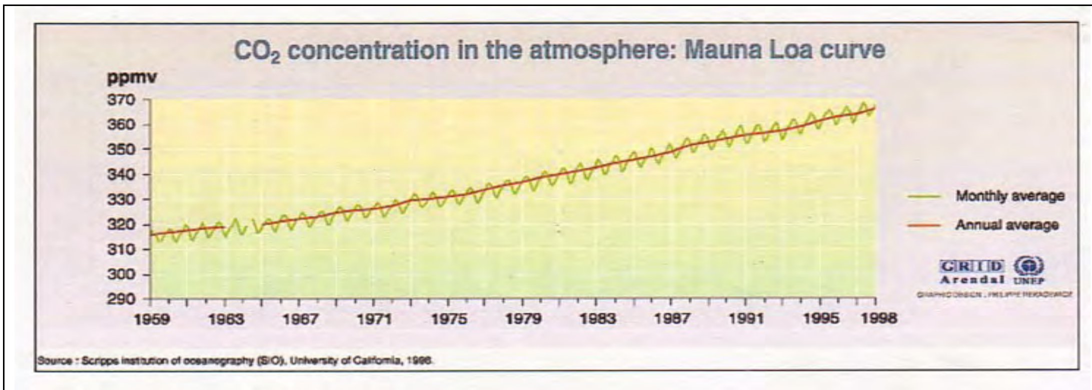


Figure 2.1: Mauna Loa Curve, concentration of CO_2 in the atmosphere (Source: University of California 1996)

In 1987, the Brundtland Report, also known as ‘Our Common Future’, linked economic development and the need to sustain it without depleting natural resources or harming the environment. This report provided a key statement on sustainable development, defining it as:

“Development that meets the need of the present without compromising the ability of future generation to meet their own needs” (Brundtland 1987, p. 43).

The Brundtland Report was concerned with securing global equity and the redistribution of resources towards poorer nations, whilst encouraging economic growth. The report also suggested that equity, growth and environmental maintenance are possible and that each country is capable of achieving its full economic potential without diminishing its resources. This report also highlighted three fundamental components of sustainable development: environmental protection, economic growth and social equity. The environment should be conserved and our resources enhanced by progressively changing the traditions in which we develop and use technologies. Developing nations must be allowed to meet their basic needs of employment, food, energy, water and sanitation. If this is to be done in a sustainable manner, there is a specific need for a sustainable level of population. Economic growth should be encouraged and developing nations should have the same growth opportunities as developed nations.

In 1988, the World Meteorological Organization (WMO) and the United Nations Environmental Program (UNEP) established the Intergovernmental Panel on Climate Change (IPCC). The purpose of the IPCC was to evaluate the state of knowledge on various aspects of climate change, including the science, environmental and socio-economic impacts and response strategies. The IPCC is recognized as the most authoritative international source of scientific, technical and socio-economic advice on climate change issues. It completed the first Assessment Report in August 1990, which was used as the basis for negotiating the United Nations Framework Convention on Climate Change (UNFCCC). The UNFCCC organized the United Nations Conference on Environment and Development (UNCED), which took place in 1992 in Rio de Janeiro, Brazil. The main objective was to stabilize greenhouse gases in the atmosphere to a level that would prevent anthropogenic interference with the climate system. Representatives from developing nations emphasized the importance of their right to economic development and argued that industrialized nations have special responsibilities to stabilize greenhouse gas emissions.

Responding to broad concerns about increasing concentrations of greenhouse gas emission in the atmosphere, resulting in global warming of the planet, most nations of the world joined in 1992 to sign the United Nations Framework on Climate Change. This included: a legally non-binding voluntary assurance that major industrialized nations would reduce their greenhouse gas

emission to 1990 levels by the year 2000, and that all nations would undertake voluntary actions to measure, report and limit their greenhouse gas emissions.
In the second Assessment Report of the IPCC (1995) the summary stated:

- Climate has changed over the past century;
- The balance of evidence suggest a discernible human influence on global climate;
- Climate is expected to continue to change in the future as the concentration of greenhouse gases in the atmosphere increases;
- For many regions and systems, the effects of climate change are likely to be adverse;
- There are still many uncertainties.

Scientific evidence points out that human activity is having an adverse impact on the global climate system, including contributing to global warming. It also became apparent that major nations would not meet the voluntary arranged targets by 2000. The parties to the treaty of the UNFCCC decided (in 1995), that it would be necessary to enter into a legally binding treaty rather than a voluntary agreement to reduce greenhouse gas emissions.

The objective of the Kyoto Climate Change conference was to enter into a legally binding international agreement, where all participating nations are committed to reducing global warming and greenhouse gas emissions. The protocol was initially adopted at the Kyoto Climate Change Conference on December 11, 1997 and took force on February 2005. The five principal concepts of the Kyoto Protocol (Fletcher 2004) were:

- Commitments to reduce greenhouse gases that are legally binding for Annex 1 countries (38 developed nations), as well as general commitments for all member countries;
- Implementation to meet the Protocol’s objectives, to prepare policies and measures that reduce greenhouse gases, increase absorption of these gases and use all mechanisms available, such as: joint implementation, clean development mechanism and emissions’ trading; being rewarded with credits, which allows more greenhouse gas emission at home;
- Minimize impacts on developing countries by establishing an adaptation fund for climate change;
- Accounting, reporting and review to ensure the integrity of the protocol;
- Compliance by establishing a compliance committee to enforce commitment to the protocol.

As from February 2009, 183 states have signed and ratified the Protocol (United Nations Framework Convention on Climate Change 2009). Under the Protocol, industrialized countries agreed to reduce their collective greenhouse gas emission by 5.2% from the 1990 level. National limitations range from: the reduction of 8% for the European Union and others, to 7% for the United States, 6% for Japan and 0% for Russia. The Kyoto Protocol permitted an emissions increase of 8% for Australia and 10% for Iceland. The United States, although a signatory to the Kyoto Protocol, has neither ratified nor withdrawn from the protocol. Australia signed the ratification on December 3, 2007 and it took effect on March 11, 2008.

The Copenhagen Climate Change conference, known as the Copenhagen Summit, was held in Copenhagen, Denmark, on December 7, 2009. The initial major goals of this conference included: greenhouse gas reduction by developed countries, agreements on how to monitor reduction commitments, and how to fund reduction of greenhouse gas emissions for developing countries.

The Copenhagen Agreement was drafted by the US, China, India, Brazil and South Africa on December 18, 2009 and was recognized, but not agreed upon, by all participating countries. The Agreement recognized that climate change is one of the greatest challenges of the present: therefore, action should be taken to keep the global temperature increase to 2ºC, to prevent the worst effects of climate change. However, this agreement does not contain any legally binding commitments that will result in reductions in CO_2 emissions (BBC News 2009).

2.2. Australia's Greenhouse Gas Emission and Response to the Climate Change Issue

It can be seen in Figure 2.2 that Australia's greenhouse gas emissions have grown from 480 million $CO_{2\text{-}e}$ in 1999, to 552 million $CO_{2\text{-}e}$ in 2009, an increase of 13.1% (Australian Government Department of Climate Change 2009).

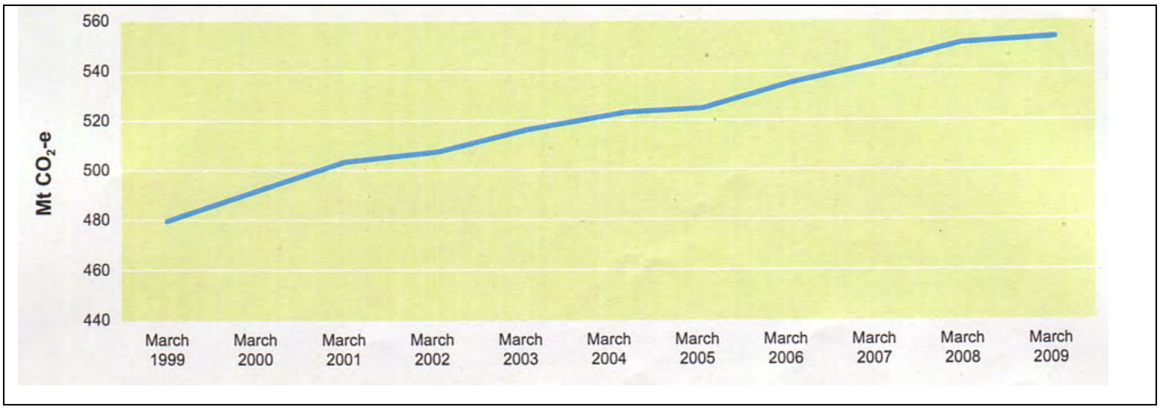


Figure 2.2: Australia's greenhouse gas emission March 1999 to March 2009 (Source: Australian Department of Climate Change 2009)

Australia's contribution to global greenhouse gas emissions is very small, at approximately 1.4% (Young 2007). However, on a per capita basis, with only 0.32% of the global population, Australia emits 1.43% of the world's CO_2 emission and is one of the highest emitters per capita in the world (Holper & Torok 2008). Table 2.1 represents a comparison of Australia's annual emission between March 2008 and March 2009 and provides a breakdown of the individual sources of greenhouse gas emissions.

Table 2.1: Australia's annual greenhouse gas emission between March 2008 and March 2009 (Source: Department of Climate Change 2009)

Category	Annual emissions through to the March quarter Mt CO_2-e [a]		Per cent change in annual emissions [d]
	March quarter 2008 [c]	March quarter 2009 [c]	
National Inventory - Annex A sectors			
Energy – Electricity	200	201	0.8%
Energy – Stationary energy excluding electricity	94	94	0.2%
Energy – Transport	80	80	-0.5%
Energy – Fugitive emissions	38	40	5.1%
Industrial processes	31	31	-0.4%
Waste	15	15	0.6%
Agriculture	90	91	0.5%
National Inventory total [b]	**548**	**552**	**0.7%**

In 1992, Australia developed the first National Greenhouse Response Strategy, involving voluntary cooperation and participation by different levels of government, industry and the community, with the aim of reducing greenhouse gas emissions (Greenhouse Challenge Agreement). Also in December 1992, Australia ratified the UNFCCC agreement. In 1995, Australia accepted and endorsed the second assessment report of the IPCC. Before the Kyoto meeting, the Australian government moved from a voluntary approach to a more proactive strategy to address the rising greenhouse gas emissions. In November 1997, the then Prime Minister of Australia John Howard announced a major statement entitled "Safeguarding the Future, Australia's Response to Climate Change". This included an $180 million package of greenhouse gas reduction initiatives and measures addressing climate change and greenhouse gas emission issues. The Australian Greenhouse Office (AGO) was established in 1998 with the role of reducing greenhouse gas emissions. In the same year the AGO published the National Greenhouse Strategy Report (Australian Greenhouse Office 1998). This report focused on three major areas:

- Implementing the awareness and understanding of greenhouse issues;
- Limiting the growth of greenhouse emissions and enhancing greenhouse sink capacity;
- Laying the foundation for adaptation to climate change.

Limiting Australia's greenhouse gas emissions (consistent with the Kyoto Protocol), was identified as the most important task for the Australian Greenhouse Office. The National Greenhouse Strategy Report focused on eight modules containing actions in response to specific problems and the anticipated results. In general, the different modules outlined actions on:

- Improving our understanding of climate change;
- Identifying climate change impacts to facilitate the development and implementation of adequate adaptive response measures;
- Communicating climate change to the community.

Module 4 (Efficient and Sustainable Energy Use and Supply) in particular, focused on the building sector and in subsection 4.8 reported improving end-use efficiency, stating that: 'Improvements to the design of commercial and residential buildings have the potential to make an important contribution to limiting Australia's greenhouse gas emissions. Building design has to be considered in its broadest sense, relating both to the architectural design of the building itself and to the wider building envelope and aspects of supervision design with impact on energy efficiency' (Australian Greenhouse Office 1998, p. 47).

In subsection 4.9, the report recommended the establishment of energy efficiency standards for residential and commercial buildings and also recommended the development of a minimum energy performance requirement for new houses and major extensions, including the application of thermal performance rating, such as the National House Energy Rating Scheme (NatHERS).

The Australian and New Zealand Minerals and Energy Council (ANZMEC), the ABCB and members from the building industries were given the task of implementing the upgrade of energy efficient building standards.

2.3. Australia's Building Industry's Strategy on the Reduction of Greenhouse Gas Emission

Buildings are a significant greenhouse emitter, as energy used in buildings accounts for about 23% of all the greenhouse emissions in Australia (Australian Sustainable Built Environment Council 2008). Figure 2.3 represents the comparison of energy consumption and greenhouse gas emission for the building sector, showing that, while the building sector consumes only 19% of all energy, it contributes 23% of all greenhouse gas emissions. Figure 2.3 shows the energy consumption and the greenhouse gas emission by the Australian building sector.

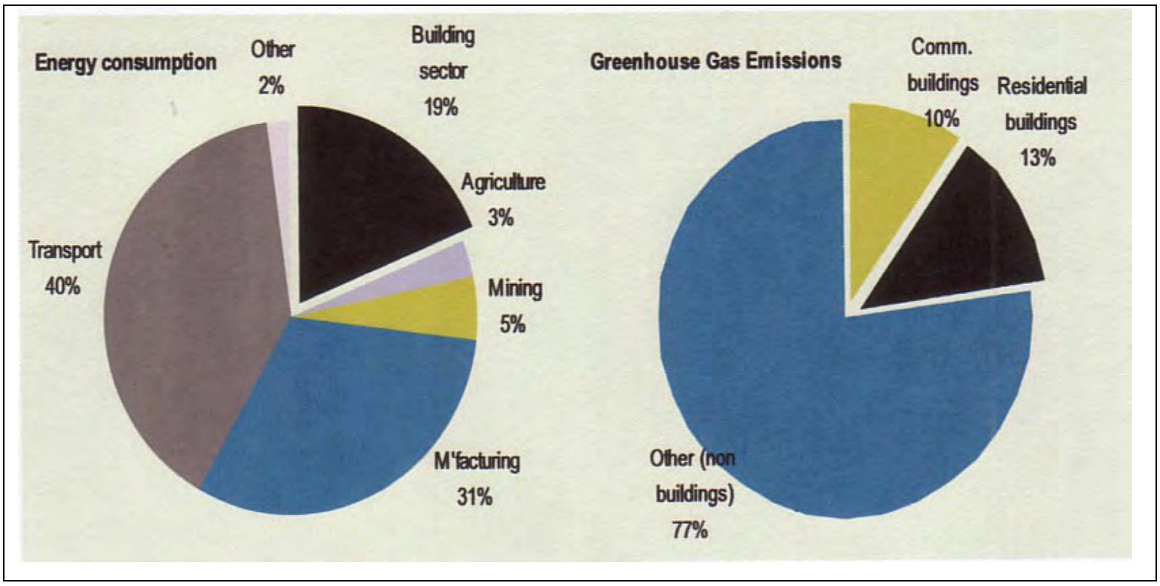


Figure 2.3: Energy consumption and greenhouse gas emission by the building sector (Source ASBEC 2008)

In November 1999, the AGO (Australian Greenhouse Office 1999) released the scoping study for minimum energy performance requirements, recommending that the appropriate mechanism for minimum mandatory energy efficiency measures was the Building Code of Australia (BCA). A Memorandum of Understanding was entered into by the AGO and the ABCB on 5 January, 2001. It was expected that the proposed energy efficiency measures for buildings would achieve significant efficiency improvements and eliminate worst practice, thereby reducing greenhouse gas emissions, while avoiding excessive technical and commercial risks and unreasonable costs (Australian Building Codes Board & Australian Greenhouse Office 2001).

The BCA is the national building code and all new buildings in Australia must comply with its requirements. The BCA is divided into two volumes: Volume 1 is generally for larger buildings, such as residential apartment blocks, commercial, industrial and public buildings. Volume 2 applies to residential buildings, such as stand-alone and attached buildings. (Class 1 and Class 10, houses, sheds, carports).

On January 1, 2003, Australia adopted the first national energy codes for the Housing Provision, Class 1 as an energy efficiency amendment of section 3.12 into the BCA. This required a minimum performance rating of 4-Stars and included: insulation standards for walls, ceilings and floors, and thermal improvements to glazing, shading, building sealing, air movement and services.

In the 2006 Edition of the BCA, the energy performance rating was increased to 5-Stars although several states: Tasmania, New South Wales and Queensland, deferred its adoption. In January 2010, Tasmania adopted the 5-star requirements for new dwellings.

2.3.1. The Building Code of Australia Energy Efficiency Requirements

The BCA provides two methods of complying with the energy efficiency requirements, namely: the Deemed-to-Satisfy Provision or presenting an Alternative Solution.

In the Deemed-to-Satisfy Provision a building solution is achieved by the building designer complying with the Deemed-to-Satisfy Provision, as demonstrated and illustrated in the BCA's construction manual, in which acceptable construction practises for specific building components are provided. To comply with the Deemed-to-Satisfy Provision in the Housing Provision Volume 2 for Energy Efficiency (Section 3.12), the building designer simply follows the description of and recommendation for typical building systems and allocated minimum thermal performance values for the following systems:

- Building Fabric (Section 3.12.1);
- External Glazing (Section 3.12.2);
- Building Sealing Section 3.12.3);
- Air movement (Section 3.12.4);
- Services (Section 3.12.5).

There are Deemed-to-Satisfy Provisions for each of the 8 climate zones in Australia. The zones are shown in the following Figure 2.4.

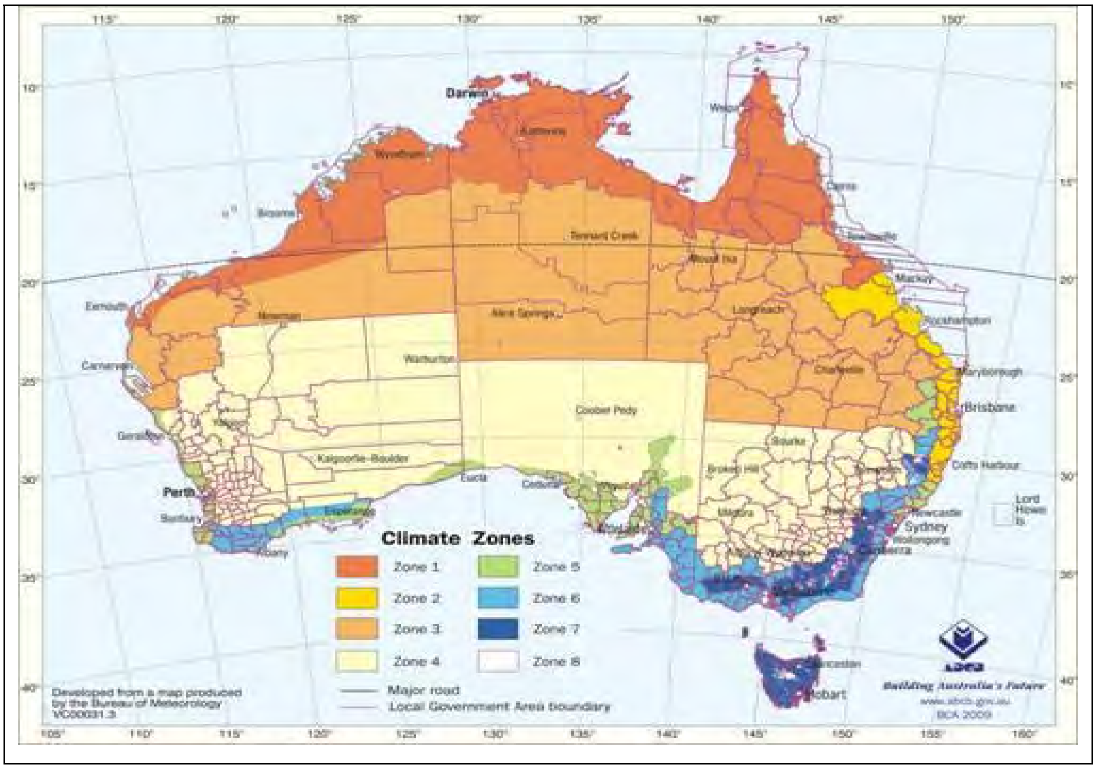


Figure 2.4: Climate zone map (Source: ABCB 2008)

The different climate zones defined by the BCA are shown in Figure 2.5 and can be briefly described as:

- Zones 1 & 2: Require cooling predominantly;
- Zones 3, 4 ,5 & 6: Require both cooling and heating;
- Zones 7 & 8: Require heating predominantly.

Climate zones	Description	Average 3 pm January water vapour pressure	Average January maximum temperature	Average July mean temperature	Average annual heating degree days
1	High humidity summer, warm winter	≥ 2.1kPa	≥ 30°C	-	-
2	Warm humid summer, mild winter	≥ 2.1kPa	≥ 30°C	-	-
3	Hot dry summer, warm winter	< 2.1kPa	< 30°C	≥ 14 °C	-
4	Hot dry summer, cool winter	< 2.1kPa	≥ 30°C	< 14 °C	-
5	Warm temperate	< 2.1kPa	< 30°C	-	≤ 1,000
6	Mild temperate	< 2.1kPa	< 30°C	-	1,000 to 1,999
7	Cool temperate	< 2.1kPa	< 30°C	-	≥ 2,000 other than Alpine areas
8	BCA Alpine areas, determined as per BCA Volume One definitions				

Figure 2.5: Climate zone map (Source: McGlynn 2006)

If the proposed building design does not comply with the Deemed-to-Satisfy Provision, an Alternative Solution process must be found and verified, using specified assessment methods. Acceptable assessments include: documentary evidence, verification methods in the BCA, expert judgement and comparison cases compared to the Deemed-to-Satisfy Provision.

The BCA states that where a building design is proposed as an Alternative Solution, the proposal must comply with the performance requirements for buildings and services, as described in Section 2.6.1. The proposal must further comply with the Verification Methods as outlined in Section V2.6. The required minimum star-rating is provided in Section V2.6.2.1 (Verification using stated value) and this section also prescribes that the thermal calculation method used must comply with the ABCB Protocol for House Energy Rating Software.

In 2004, the ABCB published the first Protocol for house energy rating software programs to facilitate the use of software under the Nationwide House Energy Rating Scheme (NatHERS). The ABCB Protocol was upgraded in 2006, to incorporate the latest second-generation house energy rating software developments. The major aim of this Protocol is to provide a legal basis for the use of house energy rating software, as a means of demonstrating compliance with the Performance Requirements (JP1 of the BCA Volume 1 and P2.6.1 of the BCA Volume 2), both through the Verification Method approach. This Protocol contains a detailed testing regime for the simulation software and all software manufacturers are required to provide evidence that results of their software programs compare acceptably with results from already complying software programs (Australian Building Codes Board 2006). For example, the Protocol in Section 6, Testing, Validation and Quality Assurance states: Simulation software must be validated in accordance with ANSI/ASHRAE Standard 140-2001 (Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs). The outcome should be within the range of results from programs that are generally accepted in the Standard.

Energy rating software has been available in Australia since 1993 under NatHERS and was designed to facilitate the rating of the thermal efficiency of dwelling design and construction in a manner that is nationally co-ordinated and consistent, and is sensitive to regional variations in climate, housing design and other factors (Delsante 1998). This scheme was developed by the State and Territory energy agencies and the Australian government, in conjunction with the CSIRO and was administrated by the Energy Efficiency Working Group (EEWG), on behalf the Ministerial Council on Energy, through the AGO of the Department of Environment, Water, Heritage and Arts (DEWHA).

The National House Energy Rating Scheme provides a framework for various computer software programs to rate the potential thermal efficiency of Australian dwellings envelopes. The scheme defines the minimum scope of assessment coverage, and mandatory setting and assessment rules that must be used by all software programs to be accredited by NatHERS. Software manufacturers must demonstrate to the NatHERS National Administrator that the software is of an appropriate standard and that it provides results that are within a certain tolerance of expected assessment rating, as described in the Software Accreditation Protocol, Part A . For example, the Protocol states that this must be accompanied by evidence that:

1. For samples of all base buildings and variation across all required climate region, 95% of the heating and cooling loads must be within a tolerance of ±5% or ±5 MJ/m², (whichever is the larger in each individual assessment), of the related Australian Government published building assessment; and
2. For the samples of all buildings and variations across all required climate regions, the tolerance of any individual heating and cooling load is ±10% or ± 10 MJ/m² whichever is greater, except where the difference is accompanied by an explanation of why the proposed tool models particular design issues better than the related Australian Government published building assessment and in these cases, the heating or cooling load tolerance is ±15% or ±15 MJ/m² whichever is greater;
3. The average star rating for the sample of all base buildings and variations across all required climate regions must be within a tolerance of ±0.2 stars, when compared to the related Australian Government published building assessment;
4. A sufficient detailed user manual exists to provide guidance for software users;
5. A training program exists to meet the needs of relevant national qualification (Nationwide House Rating Scheme National Administrator 2007, p. 6).

Further, the Protocol requires a specific output presentation, which must be in terms of energy loads of the building, adjusted for house sizes and expressed as:

- Heating and cooling loads separately in MJ/m² of calculated conditioned floor area per annum, (sensible and latent cooling loads where available);
- Total heating and cooling load, in MJ/m² of area-adjusted conditioned floor area per annum;
- An associated star-rating based on the area-adjusted conditioned floor area in relation to an area-adjusted star band score threshold for the particular climate zone.

The NatHERS website endorses three second-generation software programs, namely:

- AccuRate (current version 1.1.4.1) The Australian government developed and endorsed program (accredited May 2006);
- BERS Pro – granted provisional accreditation on November 8, 2007;
- FirstRate 5 – granted provisional accreditation on August 31, 2007.

Any of these programs can be used to demonstrate compliance with the BCA.

2.4. House Energy Rating Schemes in Other Developed Countries

Newly improved building construction techniques and energy efficient design features now make it possible to: decrease energy consumption significantly, improve thermal comfort, and at the same time decrease CO_2 emissions to the environment. While energy efficient appliances, such as dishwashers and refrigerators are now increasingly available to consumers, (indicated usually by a star-rating), the energy consumption of buildings is not as readily available to the consumer.

The energy rating of a dwelling provides information on the energy consumption and energy efficiency of a building. Energy rating is performed through measurement and simulation of the building, carried out under an experimental protocol by specialised and accredited professionals (Santamouris 2005). The energy rating provides home owners with information about predicted energy consumption energy costs and aspects of cost saving strategies through thermal improvements. House energy ratings are also now mandatory for obtaining building approvals in many countries. Energy ratings involve various measurements of the building shell, including: insulation levels, window efficiency, thermal mass and design considerations such as orientation, and ventilation The behaviour patterns of occupants controlling the internal environment are also considered such as: selecting hours of heating and cooling, thermostat settings and which part of the house is to be heated or cooled and to what temperatures.
Other aspects which rating tools may include is the emission of greenhouse gases created by operational energy and the use of embodied energy used to construct the buildings.

The use of house energy rating can be an important tool for both designers and home owners when making important design decisions or considering taking out home loans to finance the building (Ballinger 1998a). Prospective home owners can benefit from being informed about the energy efficiency of their house prior to making their purchase decisions.
There are three methods of house energy rating, all aimed at energy efficiency in buildings, namely:

- Prescriptive scheme;

- Calculation-based scheme;
- Performance-based scheme.

The prescriptive scheme specifies minimum standards for efficient building design and construction methods to qualify for a specific energy rating. The calculation-based scheme uses computer simulation software to predict the building's thermal performance and star rating.

The performance-based rating requires measured building energy consumption data to assess the energy efficiency of the house and this information is then compared to the required standards of the rating program to establish the rating of the building. Based on this classification of energy rating methods, the BCA's Deemed-To-Satisfy Provision is a typical prescriptive scheme, while the alternative solution using the Home Energy Rating tools such as AccuRate, BERS Pro or First Rate 5 is a typical example of a calculation-based scheme.

House energy rating schemes are available in many different formats, ranging from simple paper-based check lists to comprehensive computer-based performance simulations. One of the paper-based check lists (also referred as a trade-off worksheet), is called RESchek, a compliance tool developed for the US Department of Energy to determine if new buildings meet the Model Energy Code (MEC) requirements. The REScheck list covers insulation of the envelope and windows of a building, the heating and cooling system, water heating and air infiltration (US Department of Energy 1998).

Most of the rating schemes use a grading scale to rank the building. One hundred point scales and star-rating systems are the most common rating schemes, while some use only a pass or failure system. The USA has been using Home Energy Rating Schemes (HERS) since 1980 (Santamouris 2005) and there are over a hundred energy rating tools in existence (Mills 2004).

One of the major schemes is the Energy Rated Homes of America, operating in more than 18 states. This scheme includes ratings of space and water heating, ceiling, floor and wall insulation, refrigerators, freezers and air leakage and water heater tank wraps. It uses a 100 point scale of efficiency, divided into ten categories of ratings. The energy efficiency rating is based on the predicted energy consumption. One of the main reasons for employing the HERS in the USA is the possibility of obtaining more attractive Energy Efficient Mortgages (EEM). Home borrowers can expect that homes classified as energy efficient will have lower utility expenses, and therefore they can afford a higher loan repayment. Mortgage industries in the USA employ existing home energy ratings to provide loans for energy efficient improvements to houses (Farhar 2000).

The European Directive 2002/91/EC on the Energy Performance of Buildings demands that all member states of the EU include the following in their legislation on building by January 2006 (Erhorn et al. 2007):

- A methodology for the calculation of the energy performance of buildings;
- The application of minimum requirements to the energy performance of new buildings, and of existing buildings that are subject to major renovation;
- Energy certificates for buildings;
- Regular inspection of boilers, air-conditioning systems and assessment of heating systems with boilers that are older than 15 years.

All 15 European Union members have already adopted a compulsory maximum heat transmission coefficient for new buildings, (U-Value). However, there are large insulation differences for each member state. Miguez et al. (2006) reported that only a few states have gone further in their legislation and six EU states have a more complete energy rating system, which takes into consideration not only levels of building fabric insulation, but also: heating, hot water and climate control systems.

Denmark has been a pioneer of energy ratings in the EU and has subsidised energy savings for individual householders since 1981 (Miguez et al. 2006). In June 1996, it passed the adoption of the energy audit known as the "Act on Promotion of Energy and Water Conservation in Buildings" (Danish Energy Agency 1996). The Act establishes different types of energy audits for large, small and industrial buildings. Certification is compulsory for all non-industrial buildings, including: the residential and service sectors, old and new and private and public buildings. The rating system is based on energy audits undertaken by qualified specialists prior to the sale of buildings and is presented in three parts. The first part reports water and energy consumption and CO_2 emissions and provides a comparison with other similar buildings on a scaling rate from A1, (maximum efficiency) to C5. The second part is an energy plan recommending proposals for savings in energy and water use in buildings, with an estimation of the cost of investments and annual energy cost savings. The third part of the rating provides information on the current state of the building, including: size of dwelling, type of heating system, energy usage by the householder and the cost of energy to provide background evidence for the rating and energy plan.

One of the oldest HERS is in the United Kingdom: the Building Research Establishment Domestic Energy Model (BREDEM). It was developed in 1985 and the energy usage of a house calculation is based on the description of its location, dimensions, insulation and heating system.

It provides a rating on a scale of 0 to 10 (UK Building Research Energy Conservation Support Unit 1997). Calculations include the prediction of energy use for space and water heating, cooking, lighting and appliances.

The present energy rating scheme for dwellings in the United Kingdom produced by the British Planning Department, is the Standard Assessment Procedure (SAP), which is compulsory for all new buildings. It is also used to demonstrate compliance with the building regulations in Scotland and Ireland. Energy rating is based on energy costs associated with: space and water heating, ventilation and lighting. In addition, an environmental impact rating based on CO_2 emissions and a dwelling CO_2 emission rate is provided. The SAP rating is expressed on a scale 1 to 100: the higher the number, the lower the building's running costs (UK Department for Communities and Local Government 2005).
Figure 2.6 shows a SAP energy rating certificate in England with a score of 75 of 100.

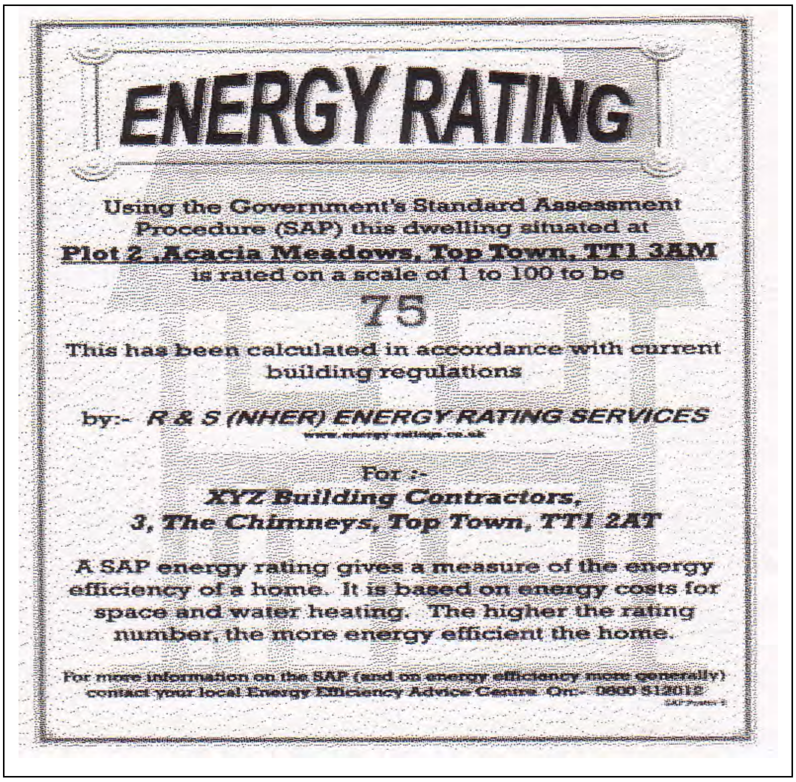


Figure 2.6: British building energy rating certificate (Source: Miguez et al. 2006)

All new homes constructed in Ireland and homes for sale or rent after January 1, 2009 require a Building Energy Rating (BER) certificate. The energy rating includes: major building components, construction type, levels of insulation, ventilation, air-tightness, heating systems (including renewable energy), and type of lighting. It covers annual energy usage for space heating, water heating and ventilation and is calculated on the basis of a standard family with a standard pattern of occupancy (Sustainable Energy Authority of Ireland 2009). The energy usage is expressed in kWh/m²annum and is represented on an A to G scale, with 'A' rated homes the most efficient and 'G' rated the least efficient. The associated Carbon Dioxide (CO_2) emission expressed in kgCO_2/m²annum is also expressed in this certificate.

The equivalent legislation in Germany is the "Energy Saving Decree", approved by the German Parliament in 2001: it applies to all new buildings and old buildings undergoing renovation and extension work. For new and renovated buildings, energy consumption is limited to 7 litres of oil per square metre per annum, which represents a 30% reduction as compared to the previous Heat Conditioning Decree of 1982 Scheme (Miguez et al. 2006). The German Energy Decree for the implementation of the Energy Performance of Buildings (EPBD) 2006 defines two energy performance assessment methods which have to be used for calculating the Energy Performance certificate values. For residential buildings, two applied standards apply, namely the DIN V 4108-6 and DIN 4701-10 (Erhorn et al. 2007). The German energy performance assessment standard for non-residential buildings (DIN V 18599) is a detailed calculation method, which includes detailed calculation procedures for many existing building systems.

Miguez et al. (2006) identified that at the time of writing only a few EU member states had taken their energy legislation any further. In fact Austria, Spain, Finland, Greece and Portugal have no official building energy rating system. Furthermore, rating systems used in Belgium, Italy and Germany seem to be no more than a sophisticated version of the existing building regulation on minimum insulation requirement for wall and roof fabrics.

Only the Danish rating system can be considered to be a complete energy system, providing a rating to building on a scale. It provides more information than a simple pass or fail grade and proposes alternatives for improving the scores initially obtained. Apart from Denmark's system, only the SAP scheme in the UK provides a scale for determining building energy savings. However, it offers no guidelines for possible energy improvements to the building (Miguez et al. 2006).

2.5. Australia's House Energy Rating Schemes

House Energy Rating Schemes were introduced in Australia to reduce residential energy consumption and greenhouse gas emissions, while at the same time ensuring thermal comfort in houses by encouraging improved building envelope design (Ballinger 1998b). The first energy rating scheme in Australia was developed in the 1980s by the Glass, Mass and Insulation (GMI) Council of Australia, referred to as the Five Star Design Rating (FSDR). The design principles of a five-star home under this system were based on three fundamental building elements: glass, mass and insulation (Ballinger 1988). This scheme was adopted in Victoria, New South Wales and South Australia, but due to its limitation of a simple pass or fail approach, it was not widely accepted by the building industry. Other early energy rating tools were: the computerised evaluation model DTAP, developed for the Concord Municipal Council of New South Wales, the ACT's Government Energy Guidelines and the Victorian House Energy Rating Scheme, which later became part of the Australia's Nationwide House Energy Rating Scheme (Ballinger & Cassell 1994).

During the early 1990s, individual states in Australia attempted to develop their own house energy rating schemes (Ballinger 1991; Wathen 1992). The Victorian Scheme was based on a computer program and was found to be the most effective for the temperate climate zones, but not flexible enough for subtropical and tropical climate conditions (Wathen 1992).

In 1992, the National Greenhouse Response Strategy identified the development of a Nationwide House Energy Scheme as one of the important tasks for the residential construction sector. It was introduced in 1993 by the Australian and New Zealand Minerals and Energy Council with the aim of providing a simple rating scheme to assess the energy efficiency of dwellings for Australia's many climate conditions. A five-star rating system was chosen and the simulation program CHEETAH (developed by Delsante), was selected for the rating assessments (Ballinger & Cassell 1994).

The Nationwide House Energy Rating Scheme (NatHERS) was finally introduced in 1998 and used the CSIRO's simulation software named CHENATH, a further refinement of CHEETAH. The development of the simulation programs used by NatHERS is described in the following section.

2.5.1. History of Australia's Nationwide House Energy Rating (NatHERS) Simulation Engine.

Australia researcher from the CSIRO including Muncey, as early as 1953 were publishing methods and principles for calculating building internal temperatures, in an changing external environment (Muncey 1953). During the period form 1953 to 1969, Muncey and Spencer and other researchers from the CSIRO commenced the development of what has become the AccuRate software today. At this time they were developing the electrical analogy and the use of matrix algebra account for the multi-variate inputs required to model the heat flows in a building (Muncey & Spencer 1969, p. 228). As the capacity of computers increased and in early 1970s, the matrix heat flow model was further developed to include many more inputs, such as radiant heat flow, convective heat flow, ventilation and air heat capacity and referred to as the matrix heat flow and electrical analogy, exchanges between surfaces and internal temperatures (Muncey 1979, p. 93).

The resultant thermal performance program was called STEP (Walsh et al. 1980). This program operated only for a single zone at hourly intervals for a three day period (Williamson et al. 2009). In 1977, Pat Walsh modified the STEP program to enable ten different zones within the building to be modelled for a period of time as long as required and was renamed ZSTEP. Walsh and Spencer reported that the heat transfer analysis for ZSTEP software program is considerably complex and the area of complication included: (Walsh & Spencer 1983)

- Radiative heat transfer processes between room surfaces;
- Convective heat transfer processes between a room and between different rooms;
- Heat flow within the ground under a building;
- The time-dependent nature of the building thermal network

Walsh & Delsante further explain the mathematical model for the use of the energy utilisation analysis of buildings and the calculation of the thermal performance. They describe that:

'The building is idealised as a multi-input, multi-output linear system. The inputs or driving forces are mainly climatic in nature. The outputs are room temperature and/or room loads. A frequency response approach is firstly developed in which the system inputs and output are viewed as being sinusoidal in time. The system may thus be characterised by a number of frequency response function relating each input to each output. Such an approach can accommodate multi-zone buildings, heat flows to the building fabric, radiative heat flow between room surfaces and various other special cases.

Next a transient response approach is developed my utilizing causal linear system theory to convert each of the frequency response function for the system into so-called total zone response factors. This approach includes a determination of sensible room heating or cooling. This model represents a realistic and efficient means of simulating thermal performance of buildings'.

Over the following decades, as computer capabilities increased, and major improvements to programs were made, the following generation of the software became CHENATH, and NatHERS (Williamson 1984, Delsante 2005). During this period of time the capabilities of the software engine was improved including the following aspect: (Dewsbury 2011)

- Number of sub floor, internal and roof zones were increased to 99;
- The simulation calculated now the zone temperature for each hour of a full year;
- A climate file with hourly input parameters was introduced;

- The ground model for concrete slab-on-ground floored building was developed;
- The ground model for platform floored buildings was developed;
- A simplistic model for the calculation of heating and cooling loads was included.

In the early 1980s, the Australian Housing Research Council funded the monitoring of vacant houses and the comparison of monitored data with the prediction of a variety of simulation programs, including ZSTEP (Williamson 1984). Internal and external climatic conditions were monitored in houses situated in Melbourne, Brisbane, Townville, Rockhampton, Canberra and Longreach for a period of 14 days. Figure 2.7 shows a comparison of predicted and measured temperatures for the monitored houses in Melbourne and Rockhampton.

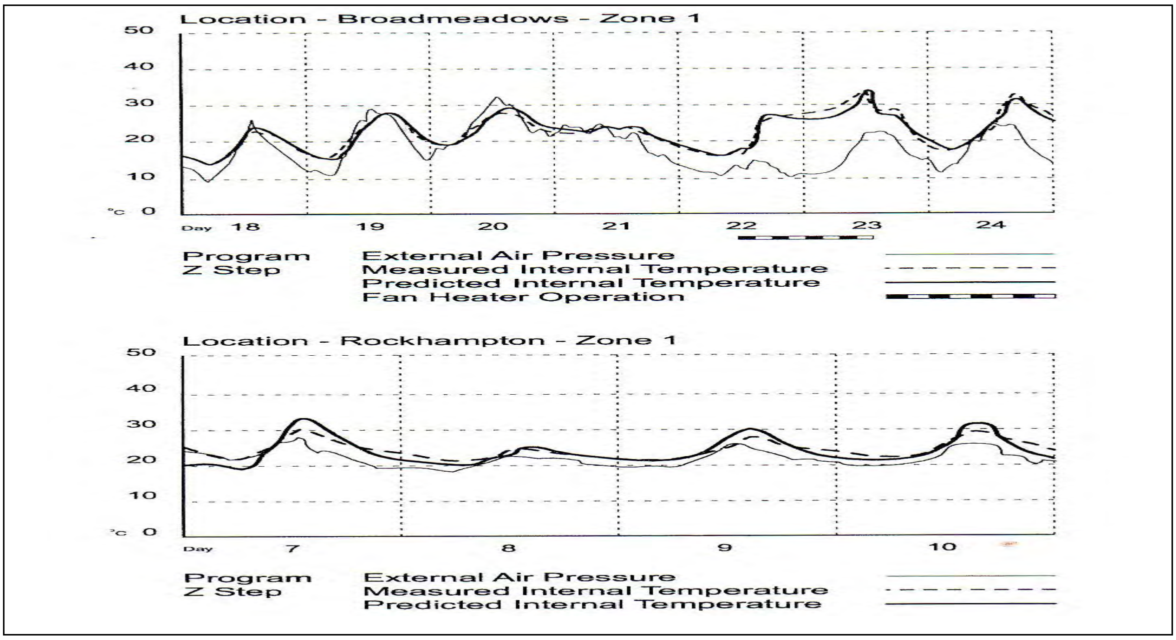


Figure 2.7: Comparison of monitored and simulated temperatures in a house in Melbourne and in Rockhampton (Source: Isaacs 2005)

The house in Melbourne was constructed on a concrete-slab-on-ground with insulated ceilings and uninsulated walls, while the house in Rockhampton was constructed using an uninsulated timber floor on an enclosed subfloor space. Isaacs (2005) remarked that the correlations between monitored and simulated temperature predictions, (as shown in Figure 2.7) were very good and this validation exercise demonstrates that the development of the ZSTEP calculation engine had not simply been a theoretical application, since simulations have been checked against houses measured in different climates of Australia.

With the introduction of micro-computers in the 1980s, ZSTEP3 was created to run on a PC-compatible computer with a text-based data entry system. This version was released as CHEETAH. It could calculate hourly temperatures and heating and cooling loads for up to ten zones of a building (Ballinger & Cassell 1994). An added feature of CHEETAH was the inclusion of a library of thermal properties of common building materials and elements.

The Nationwide House Energy Rating Scheme (NatHERS) was introduced in 1998 and the simulation engine was an upgraded version of the CSRIO's CHEETAH program and referred to as CHENATH. The NatHERS software with the CHENATH simulation engine was subjected to limited empirical and inter-program validation (Williamson et al. 2009).

The International Energy Agency (IEA) Building Energy Simulation Test (BESTEST) examines the capacity of a program to model the thermal physics related to many typical building design features, such: as: thermal mass, windows, shading devices, orientation, internal gains and thermostat variation (Judkoff & Neymark 1995). In 1995, the CHENATH simulation engine was compared to the results of 8 reference programs for the validation of a simple model test building. The model building used is a simple box with a floor area of 48m², a double-glazed window facing the equator (12m²), and windows east and west facing (6m² each) and either light-weight or heavy-weight walls and floors (American Society of Heating Refrigerating and Air-Conditioning Engineers Inc. 2004). Delsante (1995b) reported, that CHENATH prediction of heating energy agreed 'very well' with the reference programs. He further stated that because CHENATH calculates environmental and not air temperature, it was inclined to predict high cooling energies, but its prediction of cooling energy also agreed very well with the eight reference programs.
In 1992, CHENATH simulations were also compared with measured data from three test cells with single glazing, double glazing and without glazing options. The test cells, located in England, were intermittently heated for one week in October and in a free-running mode (no heating or cooling operation) for one week in May. Twenty five other simulation programs participated in the empirical validation exercise conducted by the IEA (Lomas et al. 1994). CHENATH was tested with two glazing models and test results showed, that the new glazing model significantly improved agreement between the simulated and measured temperatures in the free-running cells for single and double glazing conditions (Delsante 1995a). Table 2.2 shows the test result comparison between the simulated CHENATH prediction and the measured data at the test cells, over a 7 day period.

Table 2.2: Maximum, minimum and mean temperatures in the free running test cells (Source: Delsante 1995b)

Glazing type	CHENATH Max (ºC)	CHENATH Min (ºC)	CHENATH Mean (ºC)	Measured Max (ºC	Measured Min (ºC)	Measured Mean (ºC)
Double (new glazing model	30.3	13.1	20.51	31.0	12.2	20.53
Double (old glazing model)	29.9	12.3	20.1	31.0	12.2	20.53
Single (new glazing model)	31.7	12.2	20.34	32.6	12.1	20.81
Single (old glazing model	29.8	10.4	18.87	32.6	12.1	20.81
Opaque	16.6	9.5	13.35	16.8	9.2	13.47

From Table 2.2 it can be seen that CHENATH predictions, especially with the new glazing model, are in very close agreement with the measured data from the test cells, with the largest temperature difference being only 0.7ºC.

Delsante (2005b) reported that NatHERS software was criticised for providing insufficient natural ventilation to maintain comfort, especially in subtropical and tropical regions of Australia. Delsante agreed that the ventilation model in the NatHERS simulation did not account for wind: direction, opening sizes and locations (both in the facade and between rooms) and the effect of ventilation. In response to various criticism of the NatHERS simulation engine CHENATH, the Australian Greenhouse Office in 2002 agreed to fund a major revamp of the software program. The CSIRO’s Manufacturing and Infrastructure Technology Division was given the task of developing the Second Generation Simulation Program, known as AccuRate.

Improvements in AccuRate included: an improved modelling of natural ventilation, roof space, subfloor space, windows, skylights, changes in the thermostat setting and times of heating and cooling, and incorporation of the effect of the colour of indoor surfaces on solar absorbance. Other upgrading included the expansion of 4 habitable zones in NatHERS to up to 99 habitable zones in AccuRate. The star-rating was increased from 5 stars to 10 stars and the climate types from 27 to 69 different climate zones. An area correction factor in AccuRate was also added. As the ratio of building surface area to floor area for a larger house is smaller when compared to a small house, larger buildings under the NatHERS program achieved a higher star rating than small buildings having the same construction. In AccuRate an area correction factor aims to achieve a balanced rating across all house sizes. The adjustment is zero for dwellings with a conditioned floor area of about 200m², positive for larger areas and negative for smaller areas. For example, for a 100m² house in Hobart the adjustment factor will decrease the heating and cooling load by about 18%, while for a large 400m² house the adjustment factor will increase the heating and cooling load by about 20%. The area correction factor was introduced to discourage the design and construction of larger houses, since in absolute terms, they consume greater amount of energy than smaller dwellings, and hence produce greater amounts of greenhouse gas emission. Figure 2.8 illustrates the area correction factor for climate zone 26, which also includes Hobart, Tasmania.

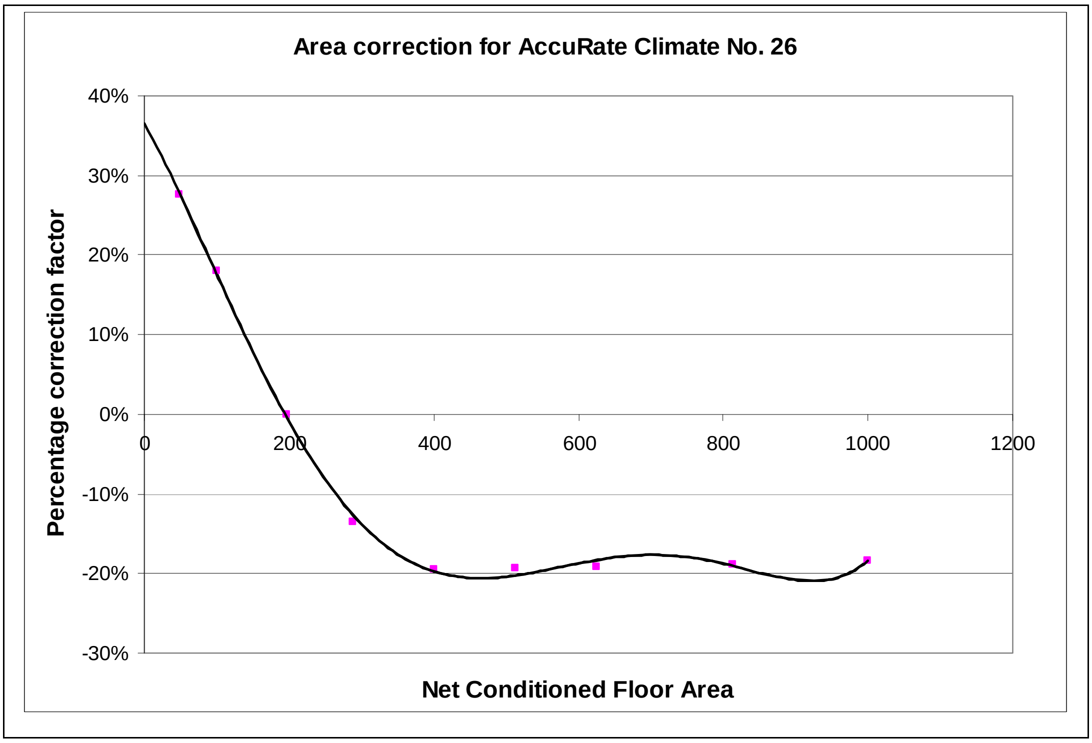


Figure 2.8: Area correction factor for climate zone 26, Hobart (Source: Isaacs 2005)

In 2004 the AccuRate simulation engine was tested against 8 international simulation programs, using the International Energy Agency (IEA) BESTEST protocol. Delsante (2005a) reports that BESTEST is a very powerful tool, because if the candidate program differs significantly from the reference results for a particular building variation, it is very likely that the candidate program is deficient in some way. However it should be noted that neither the 1995 nor the 2004 BESTEST diagnostic analysis included the testing of the natural ventilation model, as it was not part of the BESTEST reference programs. Delsante reported that overall, the BESTEST comparisons with AccuRate were very satisfactory, with the cooling energy predicted to be at the higher end of the reference program ranges. Figures 2.9 and 2.10 present the BESTEST comparisons with AccuRate.

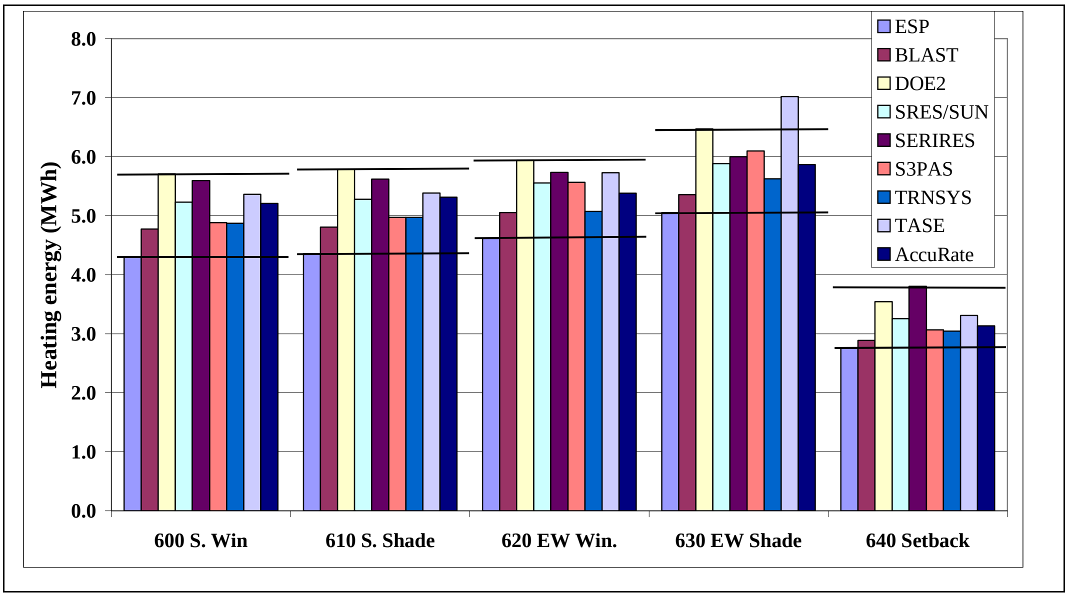


Figure 2.9: BESTEST comparison of low mass annual heating energy (Source: Delsante 2005)

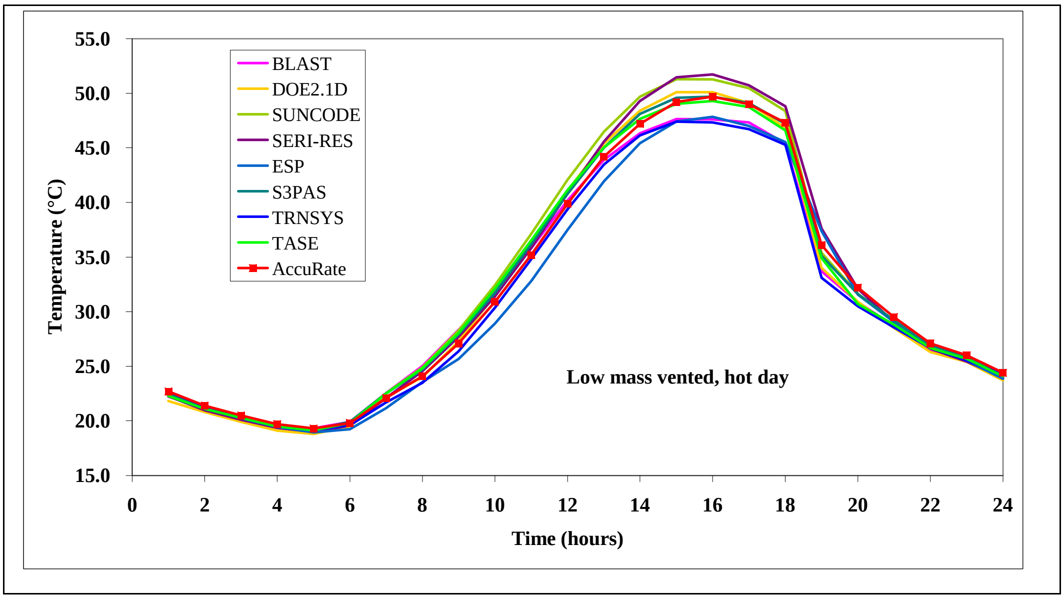


Figure 2.10: BESTEST comparison of indoor temperature in a low mass building on a hot day with sudden increase in ventilation rate at 19:00 hours (Source: Delsante 2005)

2.5.2. AccuRate Rating Tool

AccuRate is a computer software application that assesses the thermal performance of residential buildings. The software calculates energy flows within a building until balance is achieved. If the software under-predicts the temperature of a zone, the software assumes that either this additional energy is not transferred from another zone, or is correspondingly transferred to adjoining zones, depending on the other zone's temperature, fabric conductivity, emittance and infiltration values. Likewise, if the software over-predicts a zone temperature, is assumes that the zone proportionately absorbs energy for an adjoining zone, or is not transferring energy to an adjoining zone, depending on the other zone's temperature, fabric conductivity, emittance and infiltration values. Finally the software calculates the heating and cooling energy loads to maintain thermal comfort for a given location in Australia (Reardon et al. 2008). The energy assessment is determined through hourly siinmulation of the building's thermal performance, using weather data for a known building location, and taking into account the building fabric's thermal resistance and the effect of thermal mass in the building. A star rating, on a scale of 0 to 10, based on the amount of energy needed to heat and cool the house to achieve thermal comfort and the heating and cooling load (MJ/m^{2}annum), is provided in the summary report. For example, a zero (0) star rating house would have no impact on the difference between internal and external thermal conditions, while a 10-star rating house would need no additional energy for heating and cooling to achieve a thermally comfortable building (Dewsbury et al. 2009).

2.5.3. AccuRate Data Entry Process.

AccuRate requires six keys inputs which normally are referenced from architectural building plans and specifications of the housing project, namely:

a) Project Data

The location of the building is entered as the post code reference and corresponds to a particular climate zone. For example, when Hobart's postcode of 7000 is entered, the climate zone 26 will be automatically selected. The climate data chooses the typical meteorological year (TMY), a collation of selected weather data for a specific location, generated from a data bank considerably longer than a year in duration. The TMY data is the thermal simulation input for all the external weather influences on the house and includes: air temperatures, humidity, wind pattern, solar radiation and the effect of cloud cover (Delsante 2005a). The Exposure entry data describes the type of terrain and obstruction surrounding the building such as: exposed, open, suburban and protected site conditions. This data input determines the factor for the wind speed data from the weather file. Finally, the Ground Reflectance entry represents the proportion of solar radiation that is reflected by the ground immediately adjacent to the building and has a default setting of 0.2 corresponding to a grassed surface. This input needs to be changed for buildings with different adjacent ground conditions (AccuRate help file).

The postcode of the building location establishes the appropriate climate and this selects the default thermostat and thus the heating and cooling settings for the various climate zones. For example, in Hobart, which is located in climate zone 26, the thermostat settings are shown in Table 2.3 below.

Table 2.3: AccuRate thermostat setting for climate zone 26, Hobart, Tasmania (Source: AccuRate Help Manual 2008)

	Time	Temperature, °C	
		Minimum	Maximum
Living Room	0700 to 2400	20.0	23
	0000 to 0600	nil	nil
Bedroom	0000 to 0700	15.0	23
	0800 to 0900	18.0	23
	1000 to 1500	nil	nil
	1600 to 2400	18.0	23

b) Construction Details

The specific details of the external building fabric are entered in the construction master table. For example, when entering the data into the construction master table, a brick veneer wall comprises individual elements of 10mm plasterboard, a 90mm cavity with 88mm bulk insulation (fibreglass), 40mm unventilated non-reflective air cavity and 110mm clay bricks. The specific colour and solar absorptions for the internal and external surface of the individual building elements also have to be nominated. This entry method for external building fabric is applied to external walls, including: subfloor walls, internal walls, ceilings, roof, floors, windows, doors, roof windows and skylights. Each material and thickness can be selected from the AccuRate data base and allocated accordingly.

c) Selection of Zone

Each room in the dwelling is assigned to a designated zone, including the roof space and the subfloor space. The AccuRate zone types and assumptions regarding the conditioning of zones are presented in Table 2.4 below.

Table 2.4: Time periods of heating and cooling for AccuRate (Source: AccuRate Manual 2008)

Zone Type	Assumption and comments
Living	Conditioned from 07.00 – 24.00. Daytime occupancy. No cooking heat gains.
Bedroom	Conditioned from 16.00 – 09.00. Night time occupancy.
Living/Kitchen	Conditioned from 07.00 – 24.00. Night time occupancy. Cooking heat gains included.
Other (day-time usage)	If heated or cooled, conditioned from 07.00 – 24.00. No occupancy heat gains.
Other (night-time usage)	If heated or cooled, conditioned from 16.00 – 09.00. No occupancy gains.
Roof Space	Invokes special roof-space model. Not to be used for habitable spaces, such as attic rooms.
Subfloor	Invokes special sub-floor space model. Not to be used for habitable spaces such basement rooms.
Garage	Conditioned from 07.00 – 24.00 (if heated and/or cooled)

Only one zone should be classified as type 'Living/Kitchen' and because of significant heat gains in the zone type 'Living', it is recommended that only one, (or at most two zones) that are occupied during the day, should be classified as type 'Living'.

Once all the rooms of a dwelling have been designated to a specific zone type, individual input data such as: the volume of each zone, floor height, ceiling height, heating and cooling modes, as well as various infiltration details, have to be entered into the 'common properties of selected zones' column.

Finally, a zone master table provides an overview of all room names, including specified zone types, volume of rooms and heating and the selected cooling-heating modes.

d) Shading Details:

There are two separate schemes available in the shading scheme table. They are:

- The eaves input data, which determines the eave projection and the eave offset, being the vertical distance between the edge of the eave and the top of the window;
- Other fixed-shading input data addresses fixed shading devices installed over windows, such as pergolas. A blocking factor for each month determines the percentage of solar radiation passing through the shading devices which can be varied for each month.

Once the shading data has been entered in the shading schemes, shading inputs can be selected individually from the elements' master table for walls and windows. Overshadowing by trees or objects can be directly addressed in the elements master table's input data key named 'external screens'.

e) Elements

Each zone is enclosed by the elements of building fabric and this data informs the software of the thermal processes that affect the performance of each room, including: the resistance values of wall systems, thermal losses and gains through windows and air change rates within zones.

The top section of the elements' master table, addressing the element type, includes the external wall with all associated windows, doors and opaque louvres, internal walls, floor ceiling and the roof. Each pre-allocated zone and element type is then selected and the specific construction details entered in the 'Common Properties' entry data column. For example, construction details to be entered for the external walls include: pre-selected wall type, dimensions, azimuth of the selected wall category, type of eave shading, wing wall dimensions, and external screens such as adjacent trees and buildings.

f) Ventilation

The footprint of the building and a default azimuth angle are entered into the ventilation entry table. AccuRate is informed of the final orientation of the building after all external walls and the roof have been entered, by setting the north arrow to the correct direction. The software uses this information to model the dynamics of external wind pressure on the building's envelope to determine the infiltration rate for the thermal performance simulations.

2.5.4. The AccuRate Simulation Output

The simulation models the internal and external building fabric, and identifies the local climate conditions to estimate energy requirements.

For example, for climate zone 26 (Hobart), the temperature setting in the living room is pre-set between 20ºC and 23ºC and conditioning takes place only from 7a.m. to 12p.m. Heating and cooling occurs only when the temperature exceeds 23ºC or drops below 20ºC, as shown in Figure 2.11.

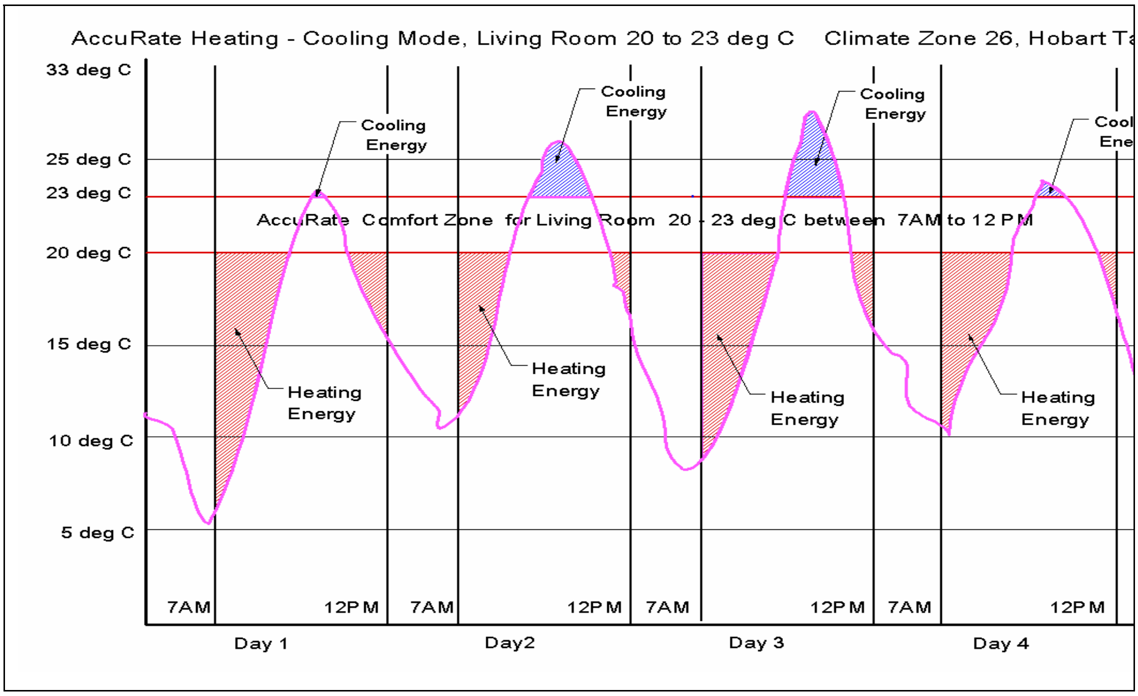


Figure 2.11: AccuRate heating and cooling energy requirements for the living room, climate zone 26, Hobart, Tasmania

After entering all building data into AccuRate's entry tables, the thermal simulation produces detailed text files on the hourly temperature in each zone for a complete year, resulting in a heating and cooling load assessment, and subsequently, the star rating. The star rating is a representation of annual estimated energy use per square metre of floor area for heating and cooling a house, based on assumed occupancy behaviour and the need to remain comfortable (Dewsbury et al. 2007).

The star-rating band is a sliding scale of the quantity of energy allocated to cool and heat a building in a particular climate zone of Australia, taking into account the extremes of local weather conditions. AccuRate uses a stepped star rating from zero to ten stars. Star rating bands are established for 69 different climate zones of Australia. For example, the energy required to achieve a 5-star rating in Coffs Harbour's temperate climate is 55MJ/m² per annum, whereas a 5-star rating house in the cool temperate climate of Hobart can consume 202MJ/m² per annum. The correlation of the predicted energy use and the star rating varies with climate location and the size of the building. As mentioned above, AccuRate's software provides an energy rating advantage to houses smaller than 200m², while providing an energy rating disadvantage to houses larger than 200m².

The summary report presents the Calculated Energy Requirements and the Area Adjusted Energy Requirements. The Calculated Energy Requirements represent the base simulation without the effect of the area adjustment factor, while the Area Adjustment Energy Requirement applies the area adjustment factor to the building. The star-rating issued is based on the Area Adjustment Energy Requirements. Figure 2.12 presents an example of an AccuRate summary report.

AccuRate V1.1.4.1

Nationwide House Energy Rating Scheme

HOUSE ENERGY RATING

Project Details	
Project Name: Acc	
File Name: C:\Program Files\AccuRate1.1.4.1\Projects\21.3.2007Wilson Homes Slab.PRO	
Postcode: 7000	**Climate Zone:** 26
Design Option: Base +8	
Description: R2.5 Rockwool Wall, R4.0 Ceiling, Single Glazed, No Vented Down lights, Dark Colorbond, Non-Reflective Wall Wrap, Dble Glaze Liv	

Client Details		
Client Name: UTAS - Best 5 Star house Program		
Phone:	**Fax:**	**Email:**
Postal Address:		
Site Address:		
Council submitted to (if known by assessor):		

Assessor Details		
Assessor Name: Detlev Geard		**Assessor No.**
Phone:	**Fax:**	**Email:**
Assessment Date: 12/22/2009		**Time:** 4:47:
Project Code:		
Assessor Signature:		

CALCULATED ENERGY REQUIREMENTS*

Heating	Cooling (sensible)	Cooling (latent)	Total Energy	Units
170.6	4.5	0.3	175.4	MJ/m².annum

* These energy requirements have been calculated using a standard set of occupant behaviours and so do not necessarily represent the usage pattern or lifestyle of the intended occupants. They should be used solely for the purposes of rating the building. They should not be used to infer actual energy consumption or running costs. The settings used for the simulation are shown in the building data report.

AREA-ADJUSTED ENERGY REQUIREMENTS

Heating	Cooling (sensible)	Cooling (latent)	Total Energy	Units
132.3	3.5	0.2	135.9	MJ/m².annum
Conditioned floor area			75.9 m²	

Star Rating

★★★★★★ **6.4 STARS**

Area-adjusted star band score thresholds

1 Star	2 Stars	3 Stars	4 Stars	5 Stars	6 Stars	7 Stars	8 Stars	9 Stars	10 Stars
723	498	354	262	202	155	113	71	31	0

Printed 4:47 pm, 22/12/2009 *Page 1 of 1*

Figure 2.12: AccuRate summary report

The building data report presents a detailed summary of the exterior and interior construction details and serves as a valuable checklist of all input data entered into AccuRate.

Temperature profiles can be obtained for any pre-selected zone and time of the year, by activating the Compare Run control buttons. In addition, free-running temperature profiles (no heating or cooling) can be generated by selecting the Non-Rating Mode and disabling the heating and cooling mode in the zone's common properties sub-column. Figure 2.13 illustrates the predicted free running temperature profiles during a cold 14 day winter period for the living room, bedroom and outdoors of a brick veneer house in Kingston, Tasmania.

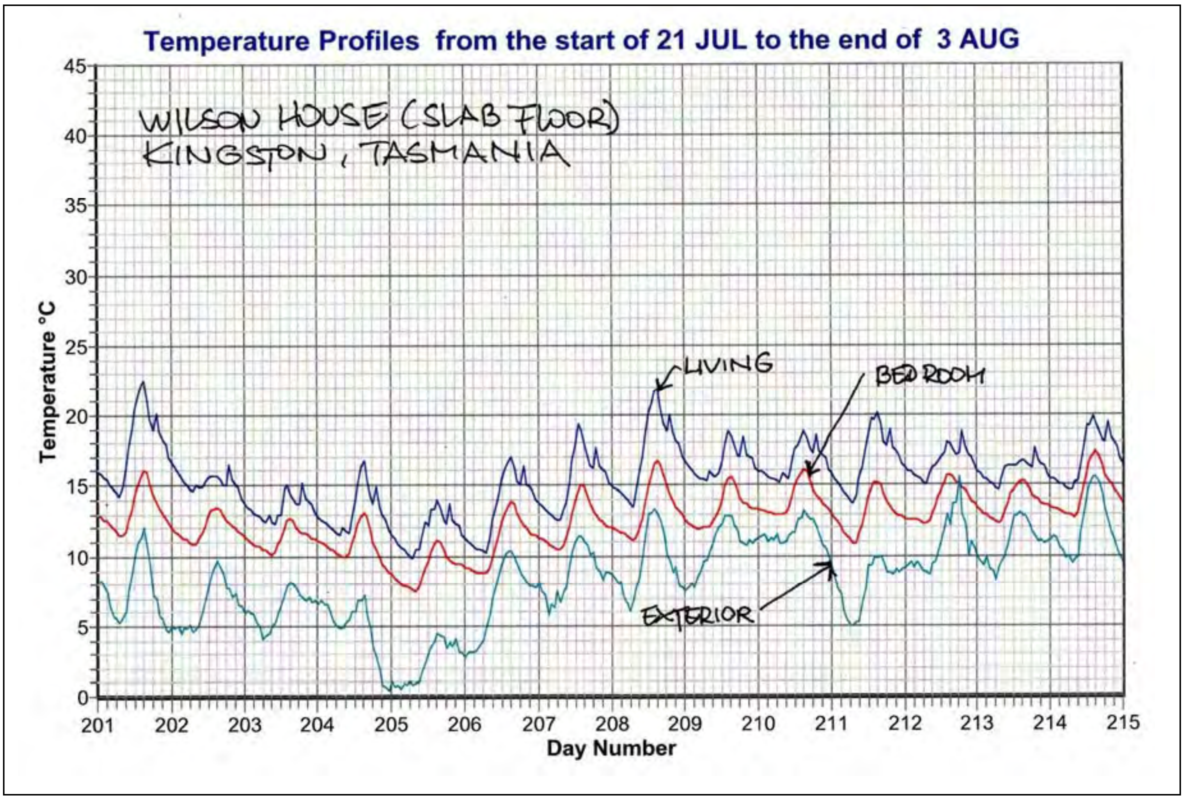


Figure 2.13: Predicted AccuRate temperature profile for a brick veneer house in Kingston, Tasmania

2.5.5. Current Australian Home Assessment Tools

There are also other building assessment tools available in Australia and these are discussed below (Iyer-Raniga & Wasiluk 2007).

- **BERS Pro** (Building Energy Rating Scheme). This rating tool is also a NatHERS software application based on the latest CSIRO HERS's calculation engine (as used in AccuRate) and it can be used for rating assessment in Australia, to demonstrate compliance with the BCA. The BERS platform uses a graphical data input process that allows designers to generate house plans graphically, rather than via data entry. Most of the information about the building is selected from existing components displayed in drawings, which makes data entry quicker and easier.
- **FirstRate 5**. This software was developed initially by the Victorian Government to accelerate the house energy rating process. It provides a simple and quick method to

assess and improve the energy efficiency of house designs. The FirstRate software is also based on the latest CSIRO HER's calculation engine and can be used in Australia for Star Rating assessment.

- **NABERS HOME** (National Australian Built Environment Rating System). The energy and water use of an existing home can be assessed using this tool. The web-based rating tool is available for the general public and is designed for ease of use. This tool focuses on the interaction between occupants and the building. NABERS provides a realistic assessment of dwelling performance. NABERS HOME rating analyses 12 months of actual energy and water use, and supplies a rating of 5 stars, with 2.5 stars representing an average household. A 5-star home is very efficient, while a 1-star home needs significant improvements. The NABERS HOME rating can only be used in homes that have been occupied for 12 months or more and this provides an excellent opportunity to check whether or not the house is performing as anticipated.
- **BASIX** (Building Sustainable Index). The NSW government introduced BASIX on July 2005 to establish a minimum standard for all new dwellings in NSW. BASIX is a planning regulation that establishes greenhouse gas emissions and water-use reduction targets for new houses, when compared to similar sized-houses in the same geographical location. BASIX addresses the building envelope thermal performance, but when determining compliance it also includes a wide range of household energy uses, such as heating and cooling appliances, lighting and water heating. BASIX uses existing tools, such as NatHERS and appliance energy and water ratings, as part of the assessment process. It sets a maximum limit for the cooling load alone and the total heating and cooling load and the simulation results must be less than the allowable maximums to achieve building compliance. BASIX uses the HERS assessment to estimate greenhouse gas emission impact, based on the thermal loads and the efficiency and type of heating and cooling appliance selected.

2.6. Conclusion

Australia's building industry's response to the need to lower CO_2 emissions resulted in the addition of the Energy Efficiency section to the BCA, and the introduction of a mandatory minimum 5-star energy rating for new dwellings in most States and Territories of Australia. A building not conforming to the 'Deemed-to-Satisfy' provision would need a thermal performance assessment using an approved simulation rating tool, such as AccuRate, to a obtain a building approval permit. As AccuRate has become a legislative energy rating tool, the simulation accuracy should be assured. In addition, many building designers use AccuRate predictions as a design tool, for determining the most cost-effective construction methods of achieving the required star rating for their building project. Therefore, predictions must be credible and reliable. Realistic energy simulations resulting in the appropriate star rating requirements are likely to reduce energy consumption and decrease CO_2 emissions resulting from the space conditioning of residential buildings in Australia.

While the AccuRate simulation program has been compared favourably to eight other international energy simulation programs under the BESTEST procedures, determining its accuracy can be achieved only through empirical validation: by comparing simulated temperatures with measured values in a building operating under normal conditions. Three test houses in Kingston, Tasmania were especially designed and constructed for the purpose of empirically validating the AccuRate simulation engine. Chapter 3 examines methods of validating building energy programs, focusing on empirical validation methods and techniques, in which simulated temperatures of buildings are compared with measured values.

Chapter 3: The Need for Validation of Building Thermal Simulation Programs

Chapter 2 pointed out that all buildings not conforming to the Deemed-to-Satisfy provision need a thermal performance assessment using an approved simulation rating tool, such as AccuRate. It is important that the software has been tested and validated, to provide the user with confidence in the program.

- Validation is a complex process which can be defined as follows: a rigorous testing of a program comprising its theoretical basis, software implementation and user interface under a range of conditions typical for the expected use of the program (Jensen 1995, p. 133).

Naylor & Finger (1967, p .92) stated that 'the reasons for avoiding the subject of verification stems from the fact that the problem of verification or validating computer models remains today the most elusive of all the unresolved methodological problems associated with computer simulation techniques. Williamson (1997) stated that this problem still exists despite numerous studies undertaken to develop appropriate methodologies. Bloomfield (1989, p. 217-222) also expressed his own definition of validation as follows: The word validation is much misunderstood. It is not feasible to verify the correctness of every path through detailed dynamic thermal simulation programs, to investigate every assumption and approximation, or to take account of every situation in which a program might be used in practice. A working definition of validation was adopted: the testing of the theoretical (physical) correctness of a program and of the mathematical and numerical solution procedures used.

3.1. Introduction

Since the late 1960s, computer programs have been used to model the thermal performance of buildings. However, until the oil embargo of 1973, these programs were mainly used for sizing heating, ventilating and air conditioning (HVAC) equipment and little emphasis was placed on predicting building envelope loads. Following the oil embargo of 1973, it was thought necessary to reduce the use of energy in buildings.

The addition of active solar components, like collectors for water and space heating, presented little difficulty for the energy simulation, since the active solar components could be added as another HVAC system.
By 1976, passive solar buildings had become popular. They made use of building strategies such as: double-glazing, thermal mass, Trombe walls and the application of a range of insulation materials. Existing programs were no longer appropriate to simulate these new conditions and a major change to existing programs was required to analyse these new, strongly solar-driven, thermally massive buildings. This initiated the development of new building energy simulation programs, and consequently the need for testing and validating these newly-developed programs (Judkoff 1988). The Solar Energy Research Institute (SERI) produced some of the first comparative validation studies of four key thermal simulation programs, namely: DOE 21, BLAST 3.0, DEROB 4.0 and SUNCAT 2.4. The building used for the validation study was a simple, direct-gain construction with a low mass and a high mass compartment and validation comparisons showed significant disagreement of up to 25% in the calculation of annual energy loads, with the occasional disagreement of up to 60% (Judkoff et al. 1983). These unexpected validation results highlighted the need for more detailed validation work, with an emphasis on the development of scientifically robust validation methodology.

In 1986, the Passive Solar System (PASSYS) project was formed by the Commission of the European Communities, with the aim of increasing confidence in environmental building performance simulation, especially in the passive solar simulation programs. The PASSYS Model Validation Development Subgroup developed a validation methodology for building energy simulation programs and tested it with the building simulation program ESP-r, which was selected as the European reference program.

In the first phase of PASSYS (1986-1989), the subgroups looked at the theory behind the different heat transfer processes within the program and worked on analytical and inter-model comparisons, including different sensitivities studies. In the second phase (1990-1991), the PASSYS sub-group developed a methodology for empirical whole model validation, further details of which are described in the following section.

To reiterate, validation of simulation programs is of the utmost importance. Rittelman & Ahmed (1985) observed that many simplified design tools, energy audits and rule of thumb tools have been generated from these simulations programs and inaccuracies within these programs will have a negative impact on building designers and public acceptance of energy efficient buildings.

This chapter focuses on the validation philosophy and methodology and concludes with a number of validation case studies, emphasizing the strength and weakness of their empirical validation methods.

3.2. Validation Methodology

According to Judkoff (1988) the three techniques for validating energy simulation software programs are:

1. **Analytical Verification**: The software predictions are compared with the exact solutions of the relevant mathematical equations. Wortman et al. (1981) highlighted limitations of this technique, namely:
    - Analytical tests concentrate only on a small part of the building simulation model;
    - Simulation model needs to be simple enough for manual analysis and calculation;
    - Simulation provides a useful indication only if the program captures the basic physics of a situation correctly.

2. **Comparative or Inter Model Comparison**: The software predictions are compared with the predictions of a 'reference set' of programs for several variations of a test building. The reference sets are programs which are already familiar to the validation procedure programs such as ESP-r, TRNSYS, BLAST and DOE2. However, it should be noted that comparative testing provides no absolute measurement of the program's accuracy: while different programs may make similar predictions, all of these predictions may be incorrect. Therefore comparative testing of programs have to pass the BESTEST or ASHRAE Standard Method of Test (SMOT) 140 procedure for validation.

3. **Empirical Validation**: The software predictions are compared with monitored data from a real building, controlled test cell or a building component located in a laboratory. The design and operation of empirical validation is based on high quality data sets, and is complex, time consuming and expensive. However, empirical validation is the only method to provide the 'real' accuracy of a simulation program, as predicted simulations are compared to actual measured data of a test building. Delsante (2005b) points to a weakness of empirical validation, observing that it is not easy, or it may not even be possible, to pinpoint the algorithms that causing discrepancies between predictions and

measurements, unless several near-identical test buildings are used as the basis for comparison.

Judkoff (1988) describes three different validation techniques and they are summarized in Table 3.1.

Table 3.1: Validation techniques (Source: Judkoff 1988)

Technique	Advantages	Disadvantages
Empirical -Test of model and solution process	-Approximate truth standard within experimental accuracy -Any level of complexity	-Experimental uncertainties Instrumentation calibration, Imperfect knowledge/ specification of experimental object (building) being simulated -High quality detailed measurements are expensive and time consuming; -Only a limited number of test conditions is practical
Analytical -Test of numerical solution process	-No input uncertainty -Exact mathematical true standard for given model -Inexpensive	-No test of model validity -Limited to highly constrained cases for which analytical solutions can be derived
Comparative (Inter-model) -Relative test of model and solution process	-No input uncertainty -Any level of complexity -Many diagnostic comparisons possible -Inexpensive and quick	-No absolute truth standard (only statistical-based acceptance ranges are possible

Judkoff notes that a validation methodology should be comprehensive and include non-empirical, as well as empirical validation techniques. He also states, that a comprehensive validation methodology should consist of: a literature review, code checking, analytical verification, inter-model comparison, sensitivity studies and empirical validation.

3.3. Data Collection Methodology

There are many levels of validation, depending on the degree of control mechanism used to control possible validation errors. Judkoff (1988) refers to seven types of typical errors one needs to be aware of. These are:

Types of external errors:

1. Differences between the actual weather surrounding the building and the weather input used by the simulation program;
2. Differences between occupancy behaviour patterns and the assumed behaviour pattern in the program;
3. User error in collecting building data files;
4. Differences between the actual built thermal and physical properties of the building and the building as simulated.

Types of internal errors:

5. Differences between the actual thermal transfer mechanism taking place in the building and the simulated model in the program;
6. Errors or inaccuracies in the mathematical solution of the program;
7. Coding errors.

To minimize sources of external errors Judkoff (1988) suggests the following approach for data acquisition within the validation process:

- Detailed meteorological and micro-climate measurements are taken on site;
- The buildings are kept unoccupied (free-running operation) to eliminate occupant behaviour errors;
- Data files are derived independently by several experienced users and then cross-checked until collective agreement is reached;
- Thermo-physical properties are directly measured on site.

To minimize sources of internal errors, Judkoff advises that a range of data must be taken to define the overall building energy performance, such as air and globe temperature. If the building is temperature-controlled, auxiliary energy measurements should also be collected. Furthermore, a range of additional data must be acquired; this is referred to as the "energy transport mechanism level, as summarized in Table 3.2 below:

Table 3.2: Energy transport mechanism level (Source: Judkoff 1988)

Conduction: measure temperature and conduction fluxes	Structural elements Glazing Ground coupling
Convection: measure tracer gas	Film coefficients: inside surfaces, outside surfaces, Air motion, infiltration, stratification
Radiation: measure radiant fluxes	Infrared surface coupling Internal surfaces External surfaces (sky temperature)
Solar	External absorption Glazing transmission & absorption Internal absorption

No analytical testing the validity of the model or comparative validation was undertaken within the scope of this study. The BESTEST comparison (Desante 2005) described how the AccuRate software compared to eight international software programs. As thermal simulation engine must by firstly validated (Lomas 1991) to establish confidence in the thermal simulation engine's capacity to calculate zone temperatures, the reminding sections of the study addresses only the empirical validation methodology, comparing predicted software's output temperatures with measured temperatures in a real building situated within a real climate.

3.4. Empirical Validation Methodology

Empirical validation can be seen as the correspondence between model predictions and reality. A number of authors have provided definitions of empirical validation in relation to thermal simulation models and several key definitions are listed, as follows:

- 'Empirical validation is seen as being concerned with examining the correspondence between reality (at least a sub-system of reality) and the model prediction' (Williamson 1995);
- 'Comparing program predictions with the corresponding results from actual buildings' (Clark & Forrest 1978);
- 'The comparison of the predictions of the model with physical reality' (Bowman & Lomas 1985);
- 'Testing the theoretical correctness of a calculation model and the numerical and mathematical procedures used to solve the resulting model' (Bloomfield 1985);
- 'Detecting whether or not a model is capable of describing reality correctly' (Palermo et al. 1991).

Lomas & Bowman (1986) state that the difficulty with empirical validation is that it involves physical experiments. They reported that in an examination of 179 existing experimental data sets for empirical validation, very few sets were of sufficiently high quality to be useful for the validation. In addition, many data sets were missing important data, such as: measuring of air infiltration; the split between the direct and diffuse solar radiation and weather data information at the test site. Very often, the physical parameters of the building materials were not measured on site and had to be obtained from handbooks. Lomas & Bowman further pointed out that if the uncertainty of the input data is large, serious errors in the simulation program may remain hidden, as good agreement between the measured and simulation data may be obtained from the faulty input data. Clearly then, the need for a high quality data set for any empirical validation project is great.

A three level empirical validation methodology was proposed by Lomas (1991b). This involves firstly modeling the building as accurately as possible, taking care not to introduce any external errors. Then the predictions must be compared with the measurements of actual building performance, without making refinements or repeating the simulations. The difference between the measurements and simulated predictions is then a true indication of the accuracy of the simulation model. The prediction should be made in ignorance of the measured results and certainly, no attempt should be made to adjust the measurements to correspond with the predictions. These are called the 'base-case' or blind-to-blind predictions and they remain fixed throughout the remainder of the validation process.

The uncertainties in the base-case prediction are then assessed in a logical and systematic way by quantifying the magnitude of all errors in both the measurements and the predictions. The measurements and predictions are compared statistically, taking these errors into account. The measurement uncertainty has to be pre-set, to determine whether the validation is satisfactory or has failed. This approach leads to a three tier empirical validation method as shown in Figure 3.1.

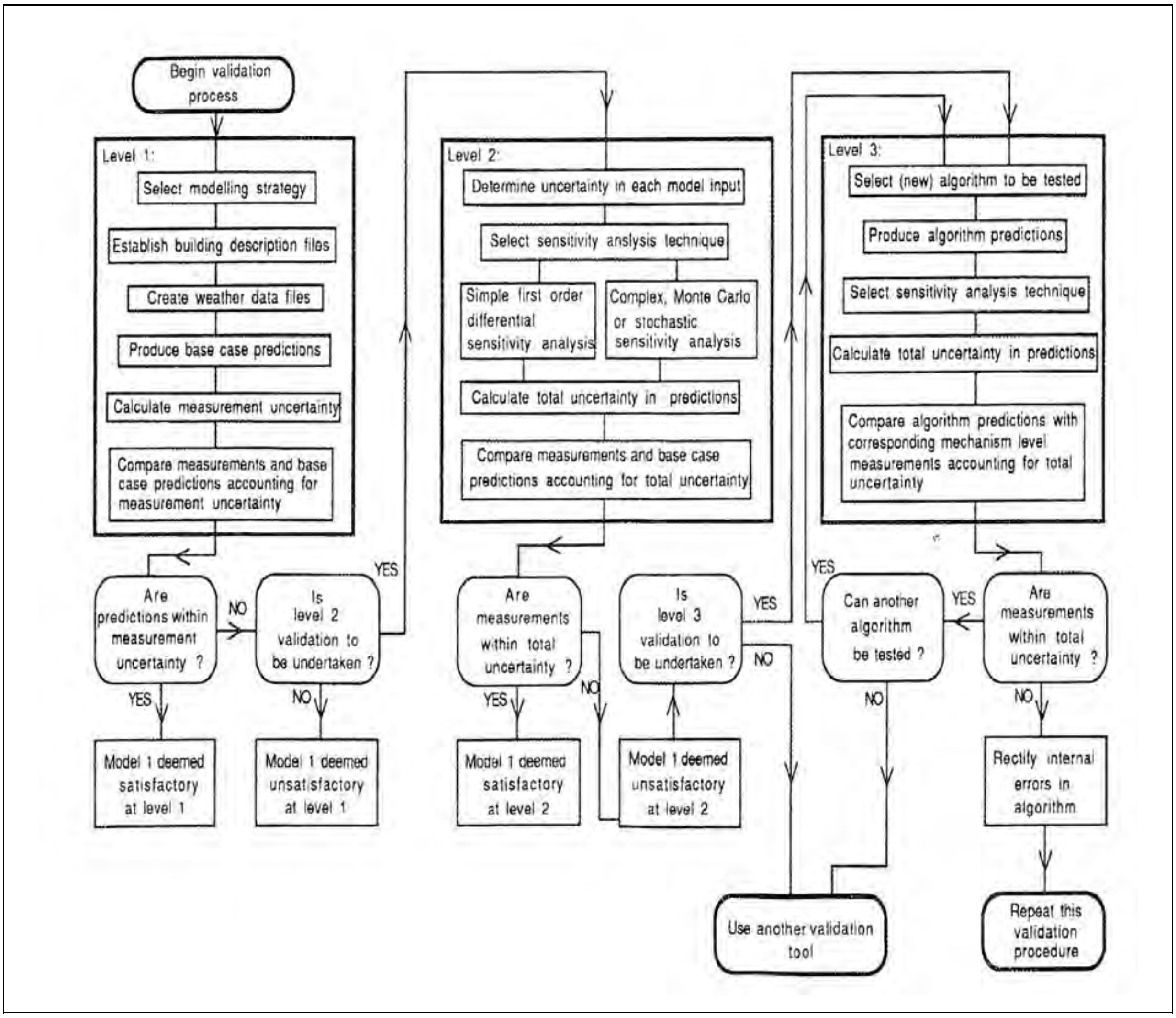


Figure 3.1: Three-level empirical validation methodology (Source: Lomas 1991)

A set of high quality data set is the basis to validate the building envelope’s load and the following criteria have been established by: Lomas et al. (1997, p. 254):

1. Structures must not include operative active solar space heating or cooling systems;
2. The weather data must have been collected at the site of the building;
3. The measured building performance data and the weather data must be available at hourly, or more frequent intervals;
4. All three major elements of the weather: air temperature, wind speed and the direct and diffuse components of solar radiation, must be measured on the site of the building for the whole validation comparison period;
5. The structure must be unoccupied; it must not contain passive solar features which cannot be explicitly modeled and each zone in the building must have independent heating and/or cooling plant and controls;
6. Measured infiltration and, where appropriate, inter-zonal air flow rates, must be available for the whole comparison period;

7. The structure must not contain features, or environmental control systems, which cannot be modeled explicitly by any of the programs being validated;
8. The data medium must be of a type which is readily usable, and close liaison with the monitoring institution must be possible.

Lomas further stated that only data sets which pass all of these criteria can to be considered 'High Quality Data Sets' (Lomas et al. 1991, p. 255).

In 1990, the PASSYS Model and Validation and Development subgroup developed a methodology for empirical model validation which indicates that 'information of program performance and cause of errors is minimized' (Jensen 1995, p. 137). The methodology comprises of six important stages:

1. Definition of scope, type and nature of the physical and numerical experiment;
2. Implementation of the physical experiment on site;
3. Processing of the measured data;
4. Performance of the simulation;
5. Analysis of the results and assessment of the sensitivity;
6. Documentation of data set and validation work.

A schematic diagram of the empirical model validation methodology is shown in Figure 3.2.

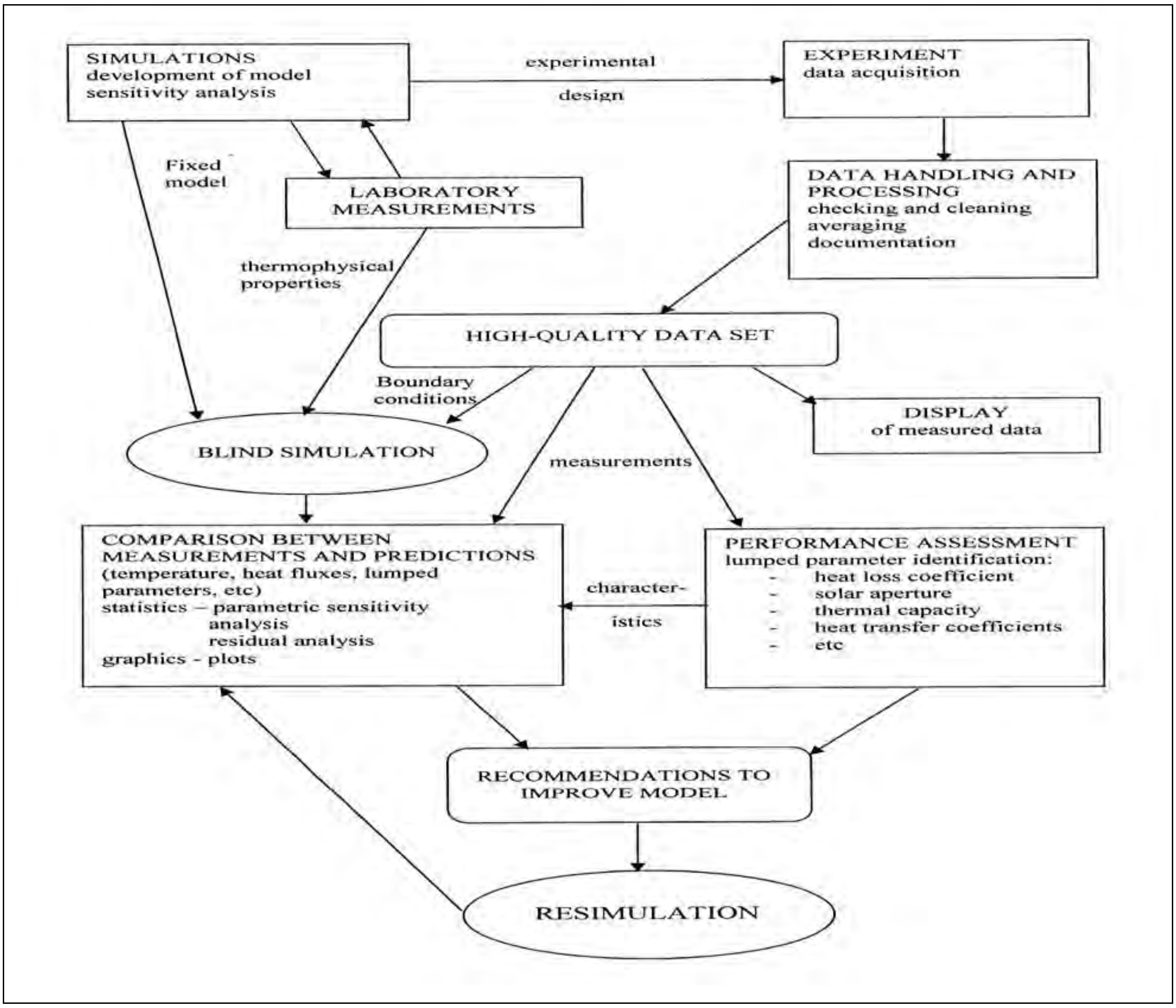


Figure 3.2: Outline of the empirical, whole model validation methodology (Source: Jensen 1995)

A validation study should be carried out by at least two teams: a leading team performing the validation exercise and a reviewing team. This provides the opportunity for the performing team to receive input and criticism from the reviewing team, including checking of the program simulation (Jensen 1995). The methodology of the six stages as derived by Jensen will be now described in more detail:

3.4.1. Definition of scope, type and nature of the physical and numerical experiment

The validation methodology and the purpose of study should be defined clearly. The thermal processes for the physical and numerical experiment should be identified and analysed. The critical sensitivity parameter of the model defined as the ‘acceptable degree of difference between the measured and simulated should also be determined’. (Jensen 1995,. p. 137).

3.4.2. Implementation of the physical experiment on site

The physical model (test component or building structure) should have been constructed. Instrumentation should be selected based on previous, verified validation studies. Jensen further states that:

- The accuracy of sensors and instrumentation should be assessed. An appropriate period with a desired range of climate variations should be selected. It is important to ensure, that the model is constructed according to the specifications, that samples of materials are obtained to enable the measurements of thermo-physical properties and that all sensors are correctly located and calibrated (Jensen 1995, p. 137).

3.4.3. Processing the measured data

A high quality set of measured data set should be collected. These data should be pre-processed, cleaned, averaged and validated. The measured data collected should be transferred into a data base for display purposes and for later comparison with the predicted values.

3.4.4. Performance of simulations

The program's modeling assumption should be studied and clarified. The input data for the computer model should be refined and adjusted, according to the model details and measured thermo-physical properties. Simulation should be performed with site-measured climate data and measured data of the physical model.

3.4.5. Analysis of the results

The measured data should be compared with the predicted, simulated data. Statistical techniques should be used to assess the resulting uncertainties in the program parameters. The uncertainties in the measured output parameters should be identified. Measurements should be compared with the predictions.

Williamson (1995, p. 2) discussed validation versus confirmation of a model and stated: 'measurement (m) are said to support a model's prediction (e) whenever m agrees with e. Only if e is a counter-instance of m (i.e. the measurements are nothing like the predictions), is the model likely to be rejected'.

However, Popper & Bartley (1983, p. 44) pointed out that this type of uncritical methodology can lead to no other conclusion than a statement such as 'the model gives good predictions for the building being investigated' or 'predictions have shown good agreement with the monitored values'. Rather than validation, Popper suggests a more critical attitude that could be stated as:

‘one looks for instances of falsification or refutation of a model. If one does not succeed we may speak of the confirmation of the model.’

The comparisons between measured and predicted values are often performed in a very simplistic way. For example, (Turing 2000) described a simple model evaluation technique: in this test, people with knowledge of a thermal performance system would be presented with two sets of information: one set generated by the computer simulation and the other from the measurement of the test building. The observer would then be asked if they could discriminate between the two sets of information. Failure to discriminate would provide confirmation of the model. When simulated data is presented in a time series (that is, hourly temperatures) and presented in a graphical form, eight techniques have been suggested by Cyert (1966) to check the correspondence of goodness-of-fit:

1. Analyse the number of turning points;
2. Analyse the timing of the turning points. The model predictions may lag or lead the measured data;
3. Analyse the direction of the turning points;
4. Analyse the amplitude of fluctuations for corresponding time segments;
5. Analyse the average amplitude over the whole time series;
6. Analyse the simultaneity of turning points for different variables;
7. Analyse the average value of variables;
8. Analyse the exact matching of variables.

Jensen (1995) stated that merely visually comparing graphs of measured and predicted values is unacceptable as a method of validation and can only give imprecise information as to what may be the cause of deviations. However, Dewsbury (2011) stated that the first visual comparison of graphical temperature patterns was helpful to decide the direction of the statistical analysis for the empirical validation for the test cells in Launceston. Within the PASSYS methodology, statistical techniques are applied to raise the standard of the validation process and to ensure that valuable information about the software performance is obtained. Temperature residual (error) analysis was one of the methods used for the test cells in Launceston (Dewsbury 2011). In this case the residuals (temperature difference between measured and simulated temperatures) were compared and analysed. While the residual analysis does not disclose what is wrong with the program, it does indicate where to look for inappropriate assumptions (Jensen 1995).

3.4.6. Documentation of data set and validation work

The validation study should be well-documented and published. Publication is essential to increase the confidence in validation methods. Recommendation for improvements to the simulation programs should be provided.

3.5. Empirical Validation Case Studies

This section examines the various approaches taken in past empirical validation studies. Many countries have carried out validation projects to improve the thermal simulation programs for residential and commercial buildings. This section initially focuses on some previous international validation studies and concludes, with the findings of some recently completed Australian validation projects.

3.5.1. International Validation Research

a) Direct Gain Test Cell Ottawa, Canada

The International Energy Agency (IEA) tested and upgraded simulation programs, as these programs were used for the generation of rules of thumb and design guidelines for building designers. The objective was to test the accuracy of a number of simulation programs against monitored data from several highly instrumented test buildings. Seven countries using twelve different simulation programs participated in the validation studies (Barakat 1986).

The IEA conducted three empirical studies on three basic designs: Direct Gain System, Trombe Wall System and Attached Sunspace. The three selected sites were located in quite different climate regions, namely:

- Direct Gain Test Building in Ottawa, Canada;
- Trombe Wall Test Cell in Switzerland;
- Attached Sunspace in the USA.

The simulation model data were compared to monitored data for a two week period from 29 December 1980 to 10 January 1981. Twelve building energy simulation programs were used to simulate the Direct Gain test cell; four were used to simulate the Trombe Wall test cell and six for the Attached Sunspace test cell.

The validation process for the Direct Gain Test cell is described below in more detail. The building (containing Units 3 and 4) was a one-storey, insulated, wood-frame building with a basement. The exterior walls and the roof had a thermal resistance of 2.1m²K/W and 3.5m²K/W respectively. The basements were used for the study of basement heat loss and the floors of the units were insulated to a resistance value of 7m²K/W. The measured air exchange rate was close to zero for all rooms.

The unit consisted of a south-facing and north-facing room with a connecting door. The north-facing room opened up onto an adjacent corridor. Each south-facing room had a south-facing window of 2.6m² glass area; each north-facing room had a 1m² window facing north. All the windows were casement windows: double glazed with an air-space thickness of 6.35mm and an R-value of 0.35m².K/W. The interior surface of all the walls and ceilings was finished with an off-white paint and the floors were carpeted.

All interior walls of the units were lined with 100mm solid cement bricks, except for the wall between the south and north rooms, consists of a single brick wall. Figure 3.3 describes the floor plan lay out for the direct gain test cell.

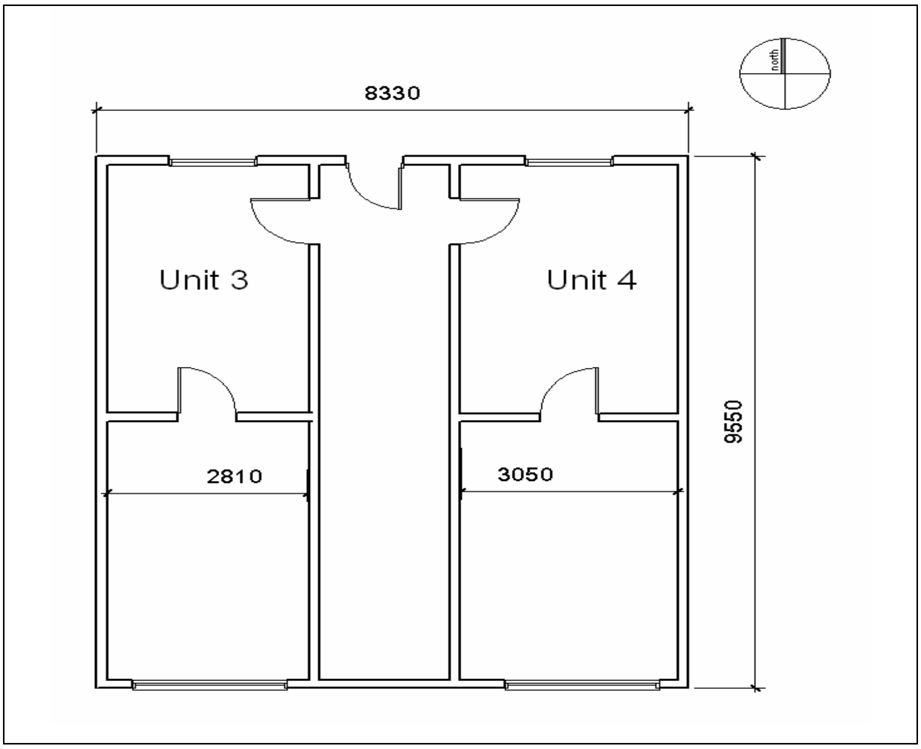


Figure 3.3: Floor plan of test buildings with two units (Source: Barakat 1986)

Each of the rooms was heated individually, with an electric wall-mounted heater controlled by a precision thermostat controller, to avoid the temperature variation caused by a conventional room thermostat. The weather data supplied were actual measurements at the test site at Ottawa, Canada.

All the simulations were performed for the unit 3 of the test building. Table 3.3 shows the comparison between the measured and predicted heating energy for the two week period, for the twelve different simulation programs.

Table 3.3: Comparison of measured and predicted heating energy for two week period (Source: Barakat 1986)

Country/Program	Total Auxiliary Heating Energy (kWh)	Difference from Measured Values %
Measured	323	-
Canada - ENCORE	309.1	-4.3
Denmark - BA4 - PASOLE - SOLMAT	312 300 323	-3.4 -7.1 0.0
Italy - SMP	312	-3.4
Netherlands – BFEP - KLI/PAS	307 297	-5.0 -8.0
Norway - ENCORE	Not reported	
United Kingdom - ESP	349	8.0
USA - BLAST - DOE-2 - SERI-RES	301.7 285 322.8	-6.7 -11.8 0.0

All the simulation models, except one, predicted the heating load for the 2 weeks period within 10% of the measured value. Two programs, SOLMAT (Denmark) and SERI-RES (USA) actually precisely predicted the heating load. Only one program's prediction, DOE-2 (USA), under-estimated the heating load by 11.8%.

Barakat (1986) stated, that considering the different approaches used by the simulation models, their different level of detail and the uncertainties of some of the input data, the agreement between the models and the measured data was very satisfactory.

b) National Institute of Standards and Technology (NIST) Passive Solar Test Facility, Gaitherburg, Maryland, USA

Program predictions of three programs, namely: ESP, HTB 2 and SERI-RES were compared with measured data from the US National Institute of Standards and Technology (Eppel & Lomas 1992).

The building is a rectangular, one-storey, slab-on-ground construction, timber-framed with the long axis running east to west. The building is divided into four cells which are separated from each other by insulated walls. Test cell 3 is a room with a conventional-sized window and test cell 4 is the direct gain cell with a south-facing glass door and a thermal storage wall at the north side. The cells and the surrounding climate were monitored for 20 days, during the period 24 January to 12 February 1984. The heating temperature thermostat was set at 20º C, and the auxiliary heat was supplied from a 3.76 kW electric heater. The floor plan of the test building is shown in Figure 3.4, below:

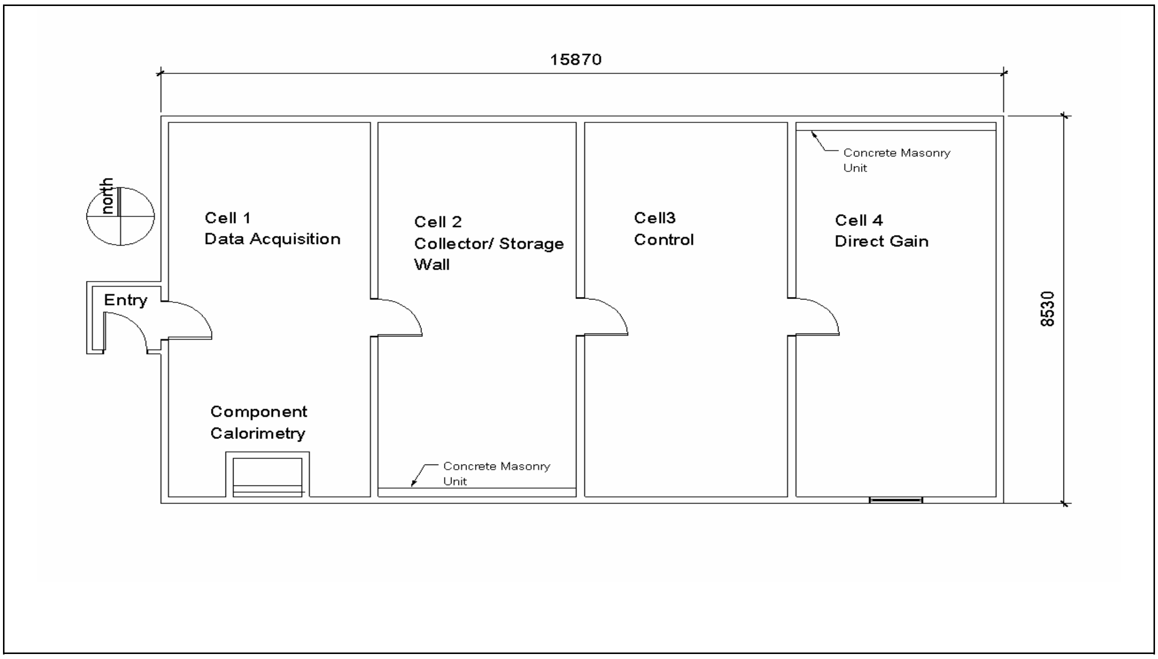


Figure 3.4: Floor plan of the NIST passive solar test building (Source: Eppel & Lomas 1992)

Data was collected only from the direct gain test cell 4. The properties of the materials were based on the ASHRAE Handbook of Fundamentals, 1981. The measured values for a 16 day comparison period, together with the base predictions of maximum temperature and total heating load for test cell 4, are shown in Table 3.4.

Table 3.4: Comparison of measured and predicted air temperatures and heating demands for the NIST passive solar test facility (Source: Eppel & Lomas 1992)

Simulation Program	Type of Temperature (ºC)	Maximum Temperature (ºC)	Total Heating Energy (kWh)
	Measured	28.0	219.1
ESP-r	Predicted Difference	26.5 -1.5	132.1 -39.3%
HTB 2	Predicted Difference	25.1 -2.9	250.5 +14.5%
SERI-RES	Predicted Difference	27.7 -0.3	209.3 -4.5%

ESP-r and SERI-RES programs both predicted maximum and minimum temperatures within 1.5ºC of measured values and according to the classification adopted in the Applicability Study (AS) work undertaken by Eppel & Lomas (1992). The maximum temperature predicted by HTB 2 was 2.9ºC lower than the measured value and they stated that this could be still classified as good agreement. The total heating energy predicted by the SERI-RES program was below the measured data by 4.5%. According to the AS classification, the heating energy prediction of both, HTB 2 and ESP-r were unsatisfactory, with the HTB 2 over-predicting by 14.5% and the ESP-r under-predicting by 39.3%.

The measurement uncertainty was determined as ±0.1% for auxiliary energy and ±0.5ºC for temperature (Mahajan 1984). As the prediction of all programs differed by more than the pre-determined measurement uncertainty, all three programs were deemed unsatisfactory and a more detailed assessment methodology was required. The comparison of predicted and measured air temperatures in test cell 4, together with a 99-precentile band, is shown in Figure 3.5. It can be seen that only SERI-RES was within the uncertainty band for its air temperature prediction, whereas ESP-r and HTB 2 were not.

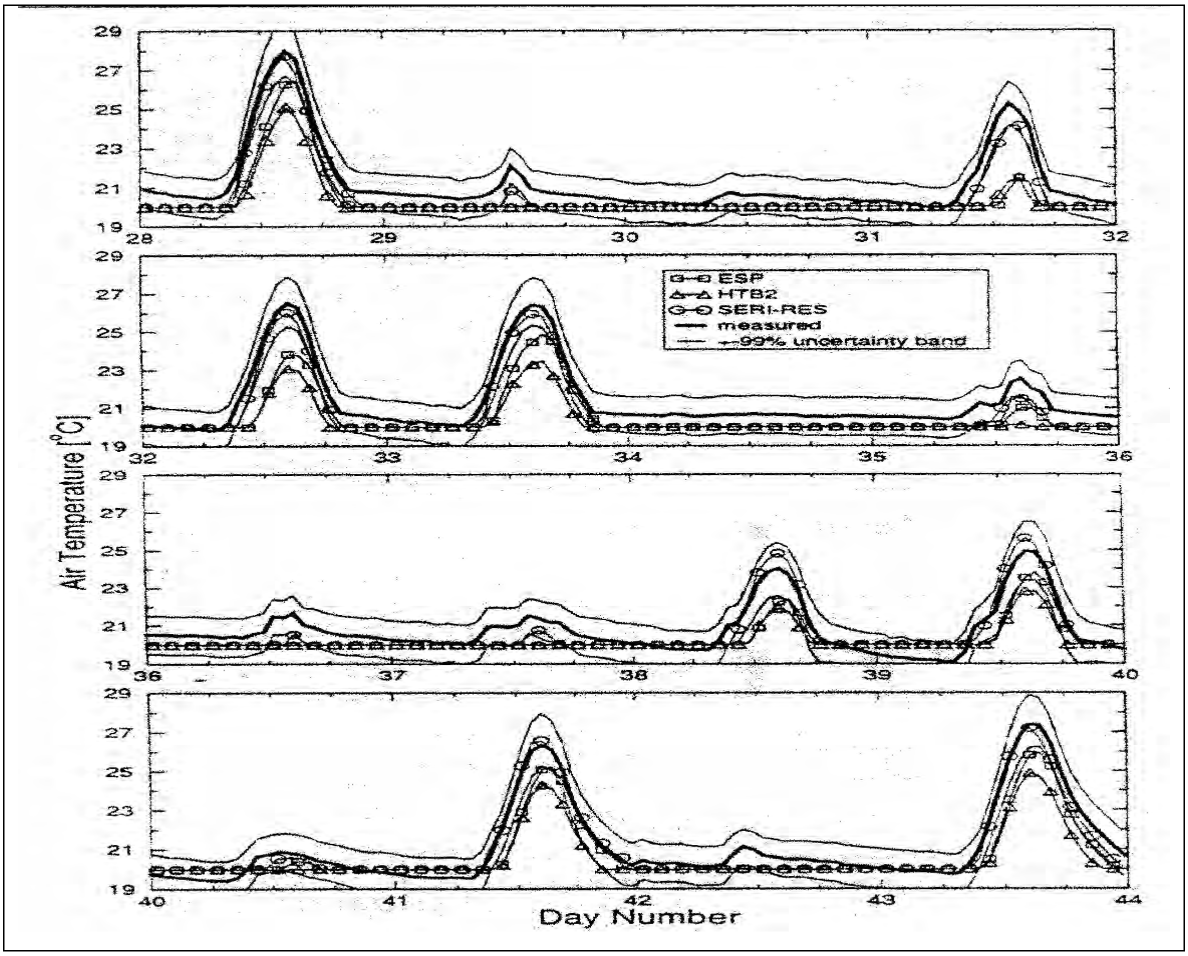


Figure 3.5: Comparison of predicted and measured air temperature (Source Eppel & Lomas 1992)

c) Test Cells England

In the 1992 predicted simulation output of the predecessor engine of AccuRate, CHENATH's simulation predictions were compared with measured data from three test cells located in England by the International Energy Agency (Delsante 1995a). The well-insulated cells were of lightweight construction, except for a 300mm concrete slab placed on top of the suspended timber floor. Hourly site-collected weather data consisted of: dry bulb temperature, relative humidity, global horizontal solar radiation, diffuse solar radiation, direct normal solar radiation and wind speed and direction. The test cells were intermittently heated for one week in October and in free-running operation for one week in March. Simulations included the incorporation of an improved glazing model with the objective of comparing the new glazing model to the old model. Table 3.5 below compares the temperature statistics of the two different glazing types with the measured values during 7 days of free-running operation.

Table 3.5: Maximum, minimum and mean temperatures in the free-running test cells (Source: Delsante 1995a)

Glazing Type	CHENATH Maximum Temperature (ºC)	CHENATH Minimum Temperature (ºC)	CHENATH Mean Temperature (ºC)	Measured Maximum Temperature (ºC)	Measured Minimum Temperature (ºC)	Measured Mean Temperature (ºC)
Single old model	29.8	10.4	18.7	32.6	12.1	20.81
Single new model	31.7	12.2	20.34	32.6	12.1	20.81

The important feature, as shown in Table 3.5, is the improved performance of the new glazing model, which predicted the minimum temperatures well, although still under-predicted the maximum temperatures. Delsante (1995a) reported that, based on this validation comparison, it was decided that the new glazing model represented a worthwhile improvement and hence it was incorporated into CHENATH. Figure 3.6 shows the graphical temperature comparison between the old and new glazing models, which clearly demonstrates the old model's consistent under-prediction of temperatures.

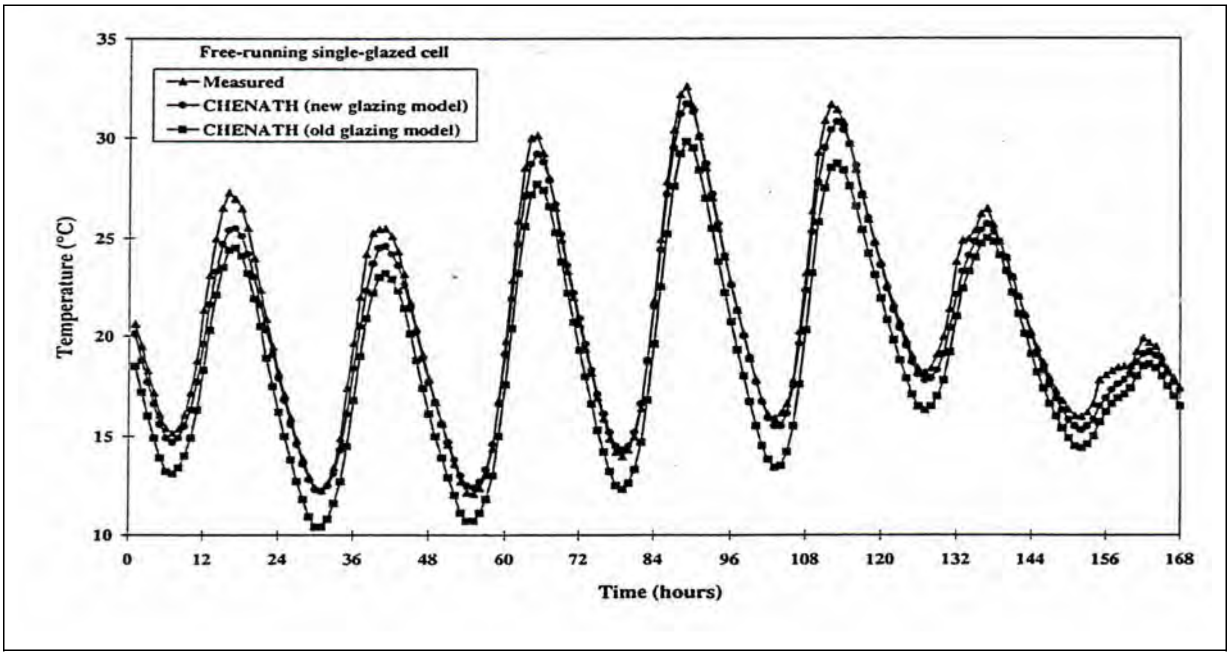


Figure 3.6: Measured and simulated temperatures for the free running single glazed test cell (Source Delsante: 1995a)

3.5.2. Australian Validation Research

a) Broadmeadows (Melbourne) and Rockhampton House, Australia

In the early 1980s the Australian Housing Research Council funded a study comparing monitored results with the prediction of the simulation program ZSTEP, a predecessor of AccuRate (Williamson 1984). Internal conditions were monitored in houses in Melbourne, Brisbane, Townsville, Rockhampton, Canberra and Longreach for periods of four to fourteen days. This also included the measurements of sufficient climate data for the purpose of empirical validation. Figure 3.7 below shows the results for Broadmeadows (Melbourne) and the Rockhampton houses.

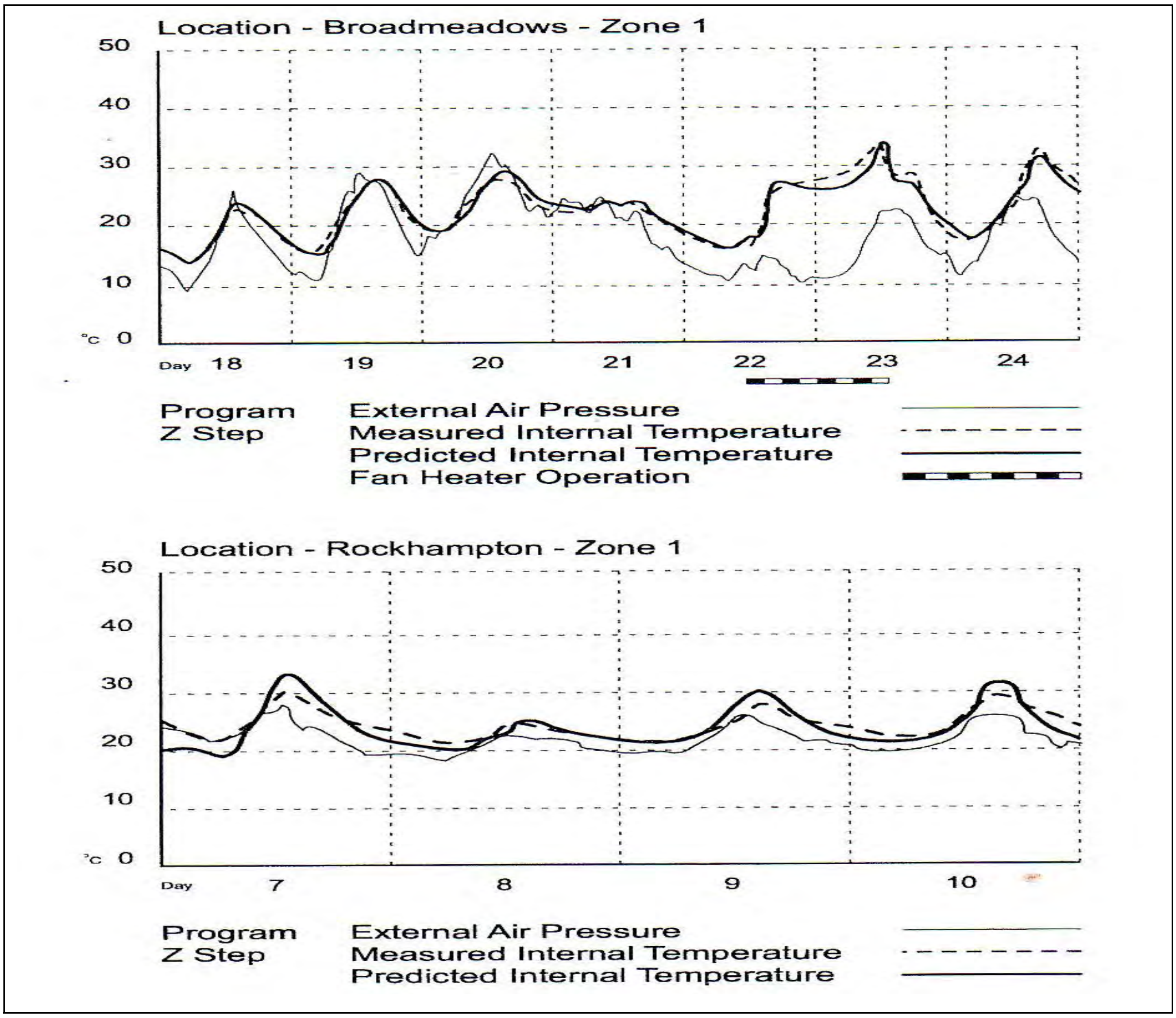


Figure 3.7: Comparison of monitored and simulated temperatures in the Broadmeadows and Rockhampton houses (Source: Isaacs 2005)

The Broadmeadows three bedroom house has a concrete slab with insulated ceilings and un-insulated walls. The Rockhampton house has a timber floor over an enclosed subfloor space and walls and ceilings that were not insulated. Isaacs (2005) reported that the correlation between the monitored and simulated temperatures was impressive, considering that the ZSTEP simulations could only model two zones and the simulation outputs were therefore, an average for conditions in several rooms, when only one or two rooms were monitored. Isaacs further states that this was not an empirical validation of ZSTEP, but rather a demonstration that the program was checked against measurements in real houses, in various climate zones of Australia.

b) Mudbrick House at Christmas Hills, Melbourne, Australia

An unoccupied mudbrick house, located at the outskirts of Melbourne was monitored by Mobile Architecture Built Environment Laboratory (MABEL) from Deakin University (Geelong), for one week in June 2005 (Desante 2006). The house, with three bedrooms and double-glazed and timber-framed windows was monitored for 4 days without heating and for 3 days with heating provided between 8.30 a.m. and to 1.30 p.m. Site weather data and indoor air and globe temperatures were monitored at 15 minute intervals in the open kitchen/dining/living area of the house. The AccuRate predicted simulation was then compared with the measured temperatures. Figure 3.8 shows the floor plan and the location of heaters and comfort carts (measuring globe and air temperatures) and the B&K 1221 thermal comfort meter using thermistors with a precision of ± 0.2K. The air temperature sensors were radiation-shielded and no sensor was exposed to direct solar radiation.

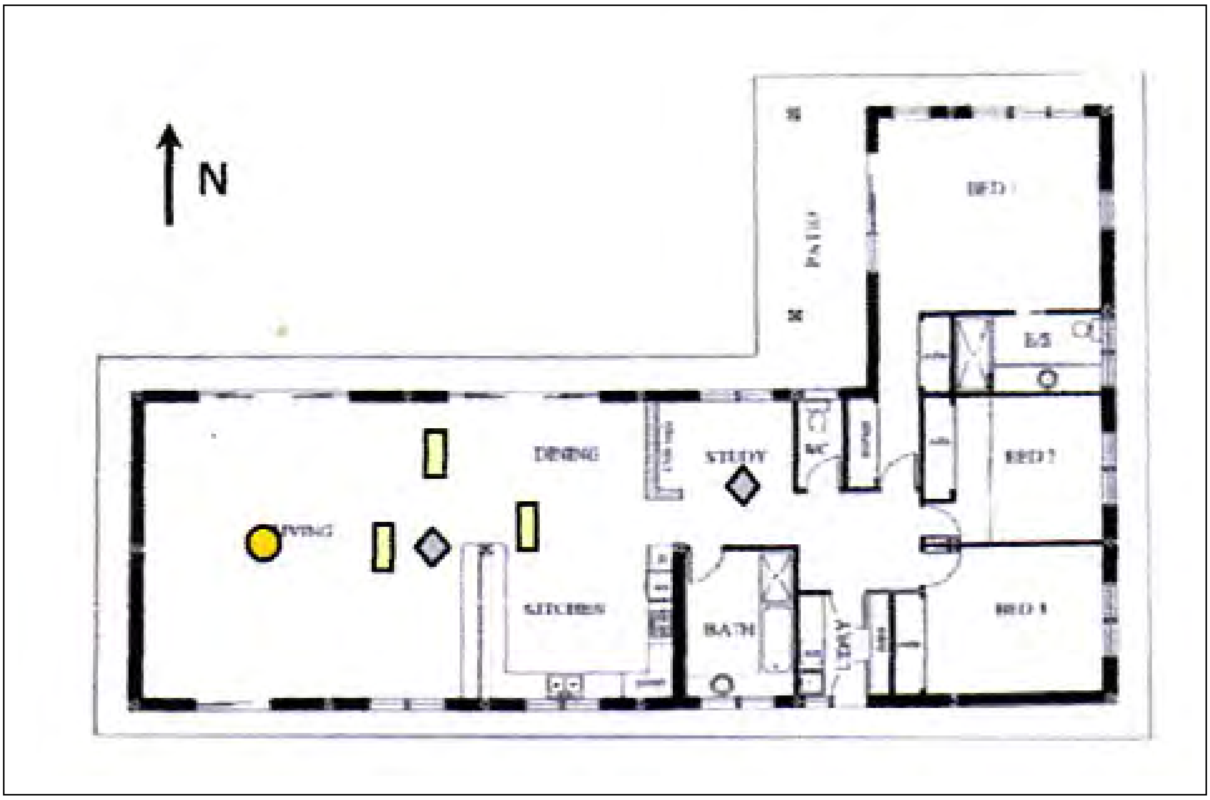


Figure 3.8: Floor plan of the mudbrick house. The rectangles indicate the positions of heaters, the diamonds the comfort carts and the circles the B&K meter (Source: Delsante 2006)

The walls of the mudbrick house consist of 245mm mud bricks with a 10mm thick external and a 5mm internal render. The floor is concrete slab-on-ground, with tiles covering the living/dining/kitchen area floors and carpets covering the bedroom floors. The raked roof is Colorbond steel with R3 bulk insulation and an internal timber lining. During the monitored time all windows and doors were closed. Weather data (diffuse, direct normal global solar radiation and air temperature) were measured on site. The infiltration rates were also measured, using the tracer gas decay technique. The mean air change rate per hour was established to be 0.33 and was used as a constant infiltration rate for the AccuRate simulation. The comparisons between the measured temperature and the AccuRate predicted simulation is shown in Figure 3.9. Delsante (2006) reported that a very good agreement was obtained, for both the heated and unheated period of the experiments.

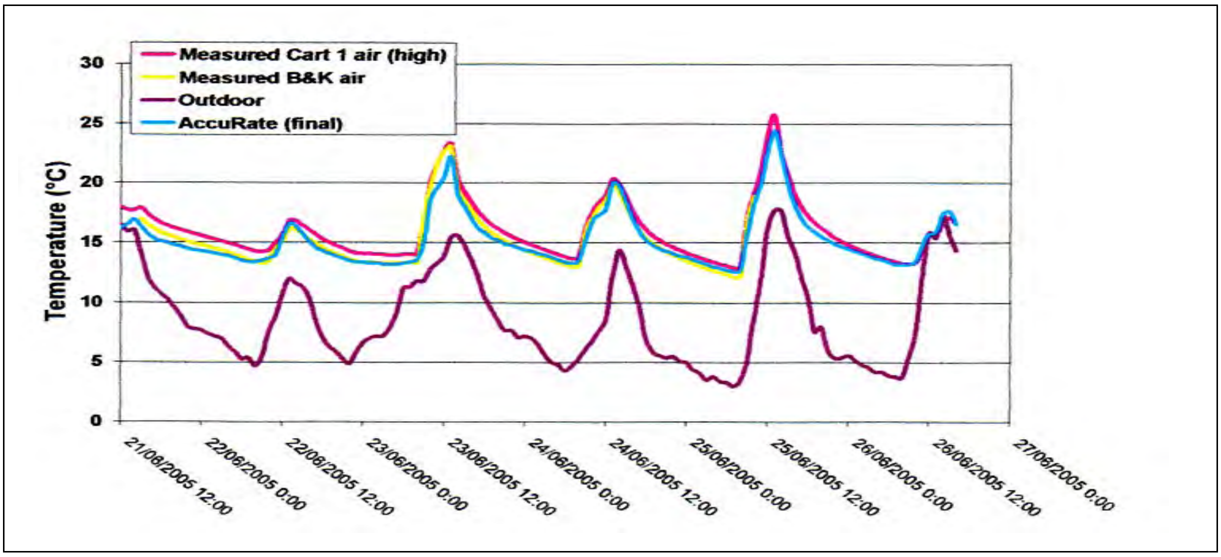


Figure 3.9: Final comparison of temperatures predicted by AccuRate with measured air temperatures (Source: Delsante 2006)

Delsante further reported that this project was not an empirical validation project. This would have required more accurate information on all the properties of the building materials and a purpose-designed test building built with meticulous attention to detail, including a rigorous data checking and error analysis process. According to Delsante these conditions could not be met because of difficulties with the measured solar radiation data and loss of data from heater number 2. Furthermore, the comparisons were done for one building only, over a short winter period, between 20 June and 26 June. This is an insufficient time period for a valid empirical validation exercise.

c) Mawson Lake Homes, Adelaide, Australia

AccuRate was validated by comparing the heating and cooling requirements of predicted AccuRate simulations with measured data for six houses in Adelaide over a two year period. This study showed that AccuRate's estimation of heating requirements compared reasonably well with measured data, but significantly under-predicted cooling energy consumption (Saman et al. 2008). To identify the changes needed to match more closely AccuRate predictions to measured data, the temperature set points used in AccuRate for the cooling thermostat setting were varied. The new AccuRate cooling parameters are listed in Table 3.6 below:

Table 3.6: AccuRate default thermostat setting and new cooling thermostat settings (Source: Saman et al. 2008)

	Cooling thermostat settings (ºC)	Temperature that triggers cooling, if cooling was not on in the previous hour (ºC)	Temperature that triggers cooling if cooling was on in the previous hour (ºC)
AccuRate Default Setting	25	27.5	27.5
New setting (a)	22	27.5	22.5
New setting (b)	23	27.5	25
New setting (c)	25	27.5	25

The results of the new cooling parameters showing predicted AccuRate annual energy use as a percentage of monitored energy use are shown in Table 3.7 below.

Table 3.7: Percentage difference between monitored data and AccuRate simulation for the various cooling parameters (Source: Saman et al. 2008)

Year	Cooling Parameter (ºC)	Heating (%)	Cooling (%)	Total (%)
2002/03	22, 27.5, 22.5	9.5	30.6	18.5
	23, 27.5, 25	9.4	-10.6	0.8
	25, 27.5, 25	9.3	-27.3	-6.3
	AccuRate Default	9.3	-46.3	-14.4
2003/04	22, 27.5 22.5	4.5	51.8	19.6
	23, 27.5, 25	4.3	8.8	5.7
	25, 27.5, 25	4.2	-9.9	- 0.3
	AccuRate Default	4.1	-33.1	-7.7

As shown in Table 3.7, the cooling parameters 23ºC, 27.5ºC, 25ºC provide the best cooling correlation for both years. Figure 3.10 shows the total average monthly heating and cooling use selected from the monitored data and the AccuRate simulated prediction for various cooling parameters.

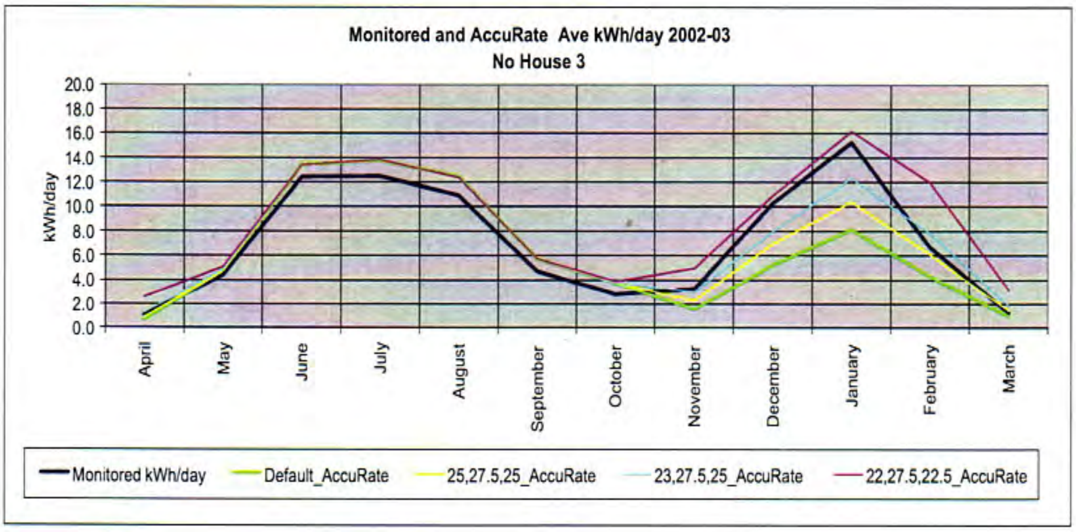


Figure 3.10: Monitored and AccuRate monthly energy use prediction for the different cooling parameters (Source: Saman et al. 2008)

Figure 3.10 illustrates, that the default setting in AccuRate shows the worst match for the cooling energy consumption, when compared to the monitored data.

At a NatHERS expert workshop held on December 14, 2007, consideration was given to a new cooling approach with:

- Separate cooling settings for assumed sleeping hours and waking hours;
- Separate cooling settings for periods after the initial trigger of air conditioning.

The workshop determined that the suggested improvements could be adopted into AccuRate, as well as the suggested new settings for Adelaide climate zone as shown in Table 3.8 below:

Table 3.8: AccuRate's suggested new thermostat setting for Adelaide (Source: Saman et al. 2008)

Usage	Time	Thermostat setting (ºC)	Trigger temperature (ºC) cooling was not on in previous hour	Trigger temperature (ºC) cooling was on in previous hour
Daytime	09.00-16.00	24	27.3	25.3
Waking	07.00-09.00 16.00-24.00	24	27.3	25.3
Sleeping	24.00-07.00	22.5	25.8	23.8

The percentage difference between the monitored data and the AccuRate predicted simulations for various cooling parameters, (including the settings), are presented Table 3.9 below:

Table 3.9: Percentage difference between monitored data and AccuRate simulation with three different settings based on a two year average data (Source: Saman et al. 2008)

AccuRate Setting	Heating	Cooling	Total
New Setting (as shown in figure 3.7)	6.5%	-7.8%	1.2%
23, 27.5 25	6.6%	-2.2%	3.3%
25, 27.5 25	6.5%	-19.7%	-3.3%

Table 3.9 indicates that the new settings now more closely match the monitored data results, with predicted cooling energy to be just 7.8% less and the total heating and cooling energy use only 1.2% more than the monitored data results. According to Saman et al. (2008), the new thermostat settings provide a good fit with the monitored data. Figure 3.11 below shows the two year average of monthly energy use from monitored data and the AccuRate predicted simulation with the new settings and the original default settings. The AccuRate's new settings predictions are now much closer to the monitored data.

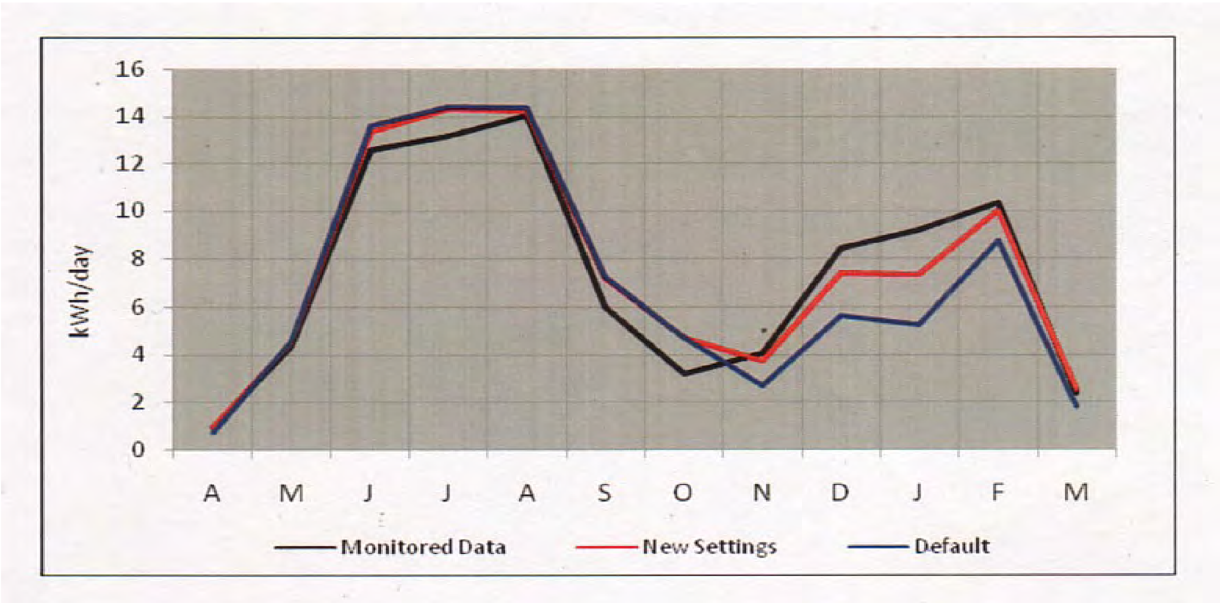


Figure 3.11: Monthly energy use from monitored data and AccuRate predictions, with new and old default settings (Source: Saman 2008)

This validation study uses only energy consumption as a comparison and did not include the validation of the building envelope by measurement comparison between simulated and measured temperatures inside the houses. Lomas (1991) stated that the software's simulation engine must be firstly validated testing the capacity to calculate zone's temperatures and therefore the validation of heating and cooling requirements can only be regarded as a secondary part of empirical validation.

d) Test Cells Launceston Tasmania

For the purpose of empirically validating the House Rating Energy software AccuRate, three test cells were built at the University of Tasmania's Newham Campus in Launceston, Tasmania (Dewsbury 2009). Three different building types, representing the most common forms of residential construction in Australia were used in the test cell construction, namely:

- Test cell 1 is an un-enclosed perimeter platform timber floor with plywood wall-cladding and sheet metal roofing;
- Test cell 2 is an enclosed platform timber floor with brick veneer walls and a sheet metal roof;
- Test cell 3 is a slab-on-ground floor with brick veneer wall cladding and a sheet metal roof.

Figures 3.12 and 3.13 show the unenclosed and the enclosed timber platform test cells in Launceston.

Figure 3.12: Test cell with unenclosed platform timber floor (Source: Dewsbury 2009)

Figure 3.13: Test cell with enclosed platform timber floor (Source: Dewsbury 2009)

The test cells are identical in size, with an internal length of 5480mm and an internal height of 2240mm; they have the same internal volume, and the assembly of roof and wall of each building are nearly identical. Each test cell has one door, but no windows. The test cells were equipped with extensive monitoring equipment and the indoor temperature was recorded at ten minute intervals over a 24 hour period.

Temperatures measured inside the test cells were taken at different heights by sensors attached to a pole at the centre of the room. Figure 3.14 shows the sensors installed at the following heights:

- Interior surface of the particle floor;

- 600mm above the floor (1/3 of room height);
- 1200mm above the floor (mid-room height);
- 1800mm above the floor (2/3 room height);
- Interior surface of the plaster board ceiling.

Figure 3.14: Temperature sensor installation at the test cells in Launceston (Source: Dewsbury 2009)

Initial AccuRate simulated and measured temperature data from the test cells during one warm week (between 15 February and 22 February 2007) and one cold week, between (15 July and 22 July 2007) were collected (Dewsbury et al. 2009). The following Figures 3.15 to 3.18 present a graphical temperature comparison between the cold and mild week for the test cell with enclosed timber floor and the test cell with the concrete slab floor construction.

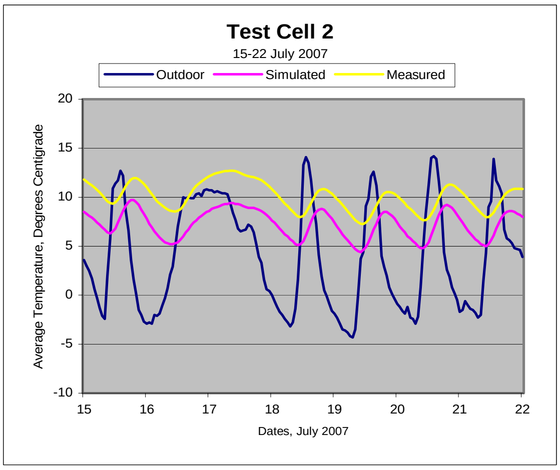


Figure 3.15: Simulated and measured indoor temperature in test cell 2 (enclosed timber floor) during a cold week (Source: Dewsbury 2009)

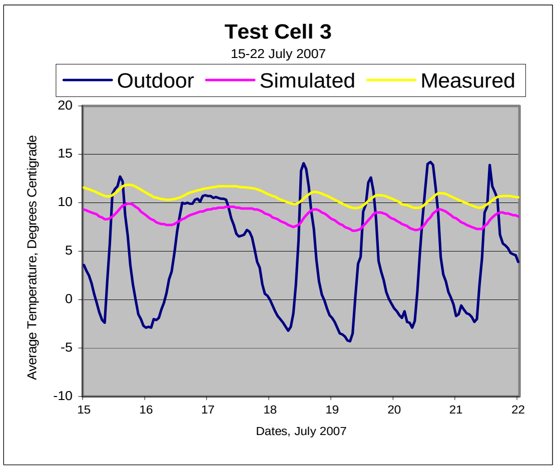


Figure 3.16: Simulated and measured indoor temperature in test cell 3 (concrete slab-on-ground floor) during a cold week (Source: Dewsbury 2009)

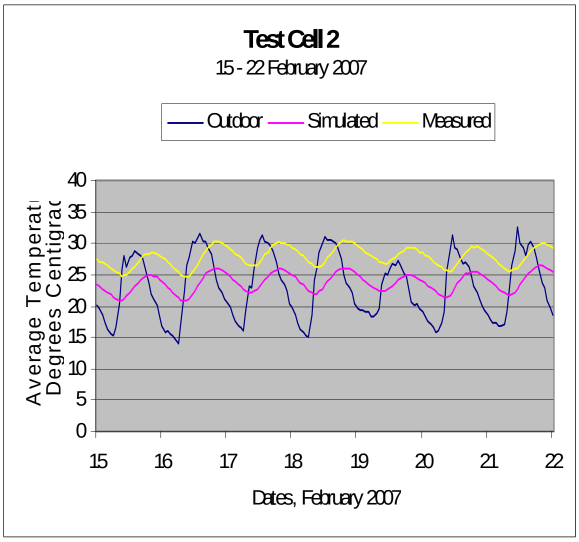


Figure 3.17: Simulated and measured indoor temperature in test cell 2 (enclosed timber floor) during a warm week (Source: Dewsbury 2009)

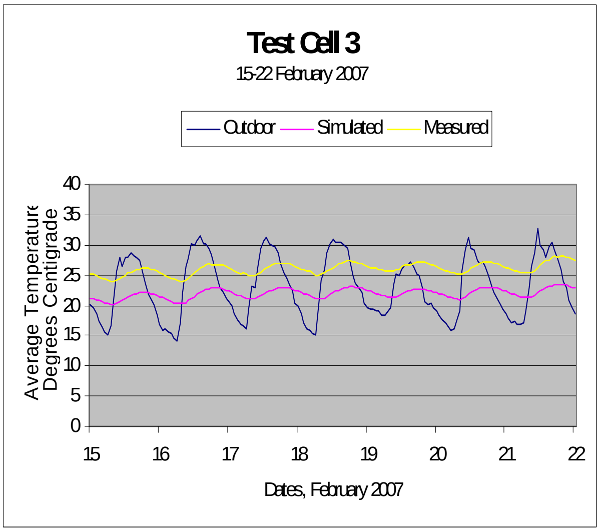


Figure 3.18: Simulated and measured indoor temperature in test cell 3 (slab-on-ground floor) during a warm week (Source: Dewsbury 2009)

In general, AccuRate simulated hourly temperatures in both test cells were lower than the measured values.

The Launceston test cell study represents the only valid empirical envelope validation project in Australia. The test cells were especially designed and constructed for the validation process and significant environmental data for the test cells were collected over a one year period. This also included the collection of site climate data over the same period.

3.6. Conclusion

Empirical validation is a complex process and it involves a rigorous testing of the simulation program based on its theoretical model. It demands a comprehensive understanding of the software operation and a set of reliable measured data in order to compare measured data with the simulation predictions of the program. According to Jensen (1995), in practice it is not possible to perform a complete validation of a program, as there are too many interlinked factors and too many possible applications to test all the combinations. It is however, possible to increase confidence in a simulation program by applying a well-documented and comprehensive validation methodology, combining several validation techniques. The predecessors of the AccuRate simulation engine, (ZSTEP in 1984 and CHENAH in 1992), were subjected to a limited number of limited empirical validation studies. They showed very acceptable results.

AccuRate's heating and cooling predictions were validated by comparing simulated data with monitored heating and cooling energy data for six Adelaide houses. The results showed realistic estimated energy consumption during the winter months, but under-estimated the actual cooling energy requirements during the hot summer months. As a result of that validation study, the temperature set points used in AccuRate for the cooling energy simulation were modified to obtain a better match with the monitored results (Saman et al. 2008).

The test cells in Launceston were specifically constructed for the validation of AccuRate software and are to date the only valid empirical validation project in Australia where a large number of environmental data was collected over a significant time period. Average hourly temperatures were compared between simulated and measured values. With the exception of the test cells in Launceston, none of the validation case studies mentioned in this chapter present an authoritative empirical validation example based on a building envelope assessment: comparing simulated room temperatures with measured values. For the purpose of assisting decision makers, only empirical validation can provide the necessary information regarding the accuracy, or at times the inaccuracy of a simulation program. This should include detailed graphical temperature comparisons and statistical analysis of simulated and empirical data.

Chapter 4 explains the methods used for the empirical validation in this project. It describes the measurement profiles and the quantity and quality of climate data needed for the purpose of empirical validation. An illustration sample of comparing simulated temperatures with measured values is also provided.

Chapter 4: Research Design and Empirical Validation Methods

4.1. Introduction

Chapter 3 pointed out that empirical validation is a complex process and involves a rigorous testing of the software simulation, based on Jensen's whole model validation methodology shown in Figure 3.2 and a set of reliable measured data, to compare the measured data with the simulation prediction of the software.

This chapter describes the research methods used in this study to carry out the empirical validation of AccuRate, the House Energy Rating Scheme's (HERS) simulation program. In the empirical validation of a simulation program two elements are essential, namely:

- A physical model that can be monitored for a selected period of time. In this project, three test houses have been designed and constructed for this purpose;
- A simulation software output, to which measured data from the physical model can be compared.

Figure 4.1 below presents the schematic diagram of the validation method applied in this project.

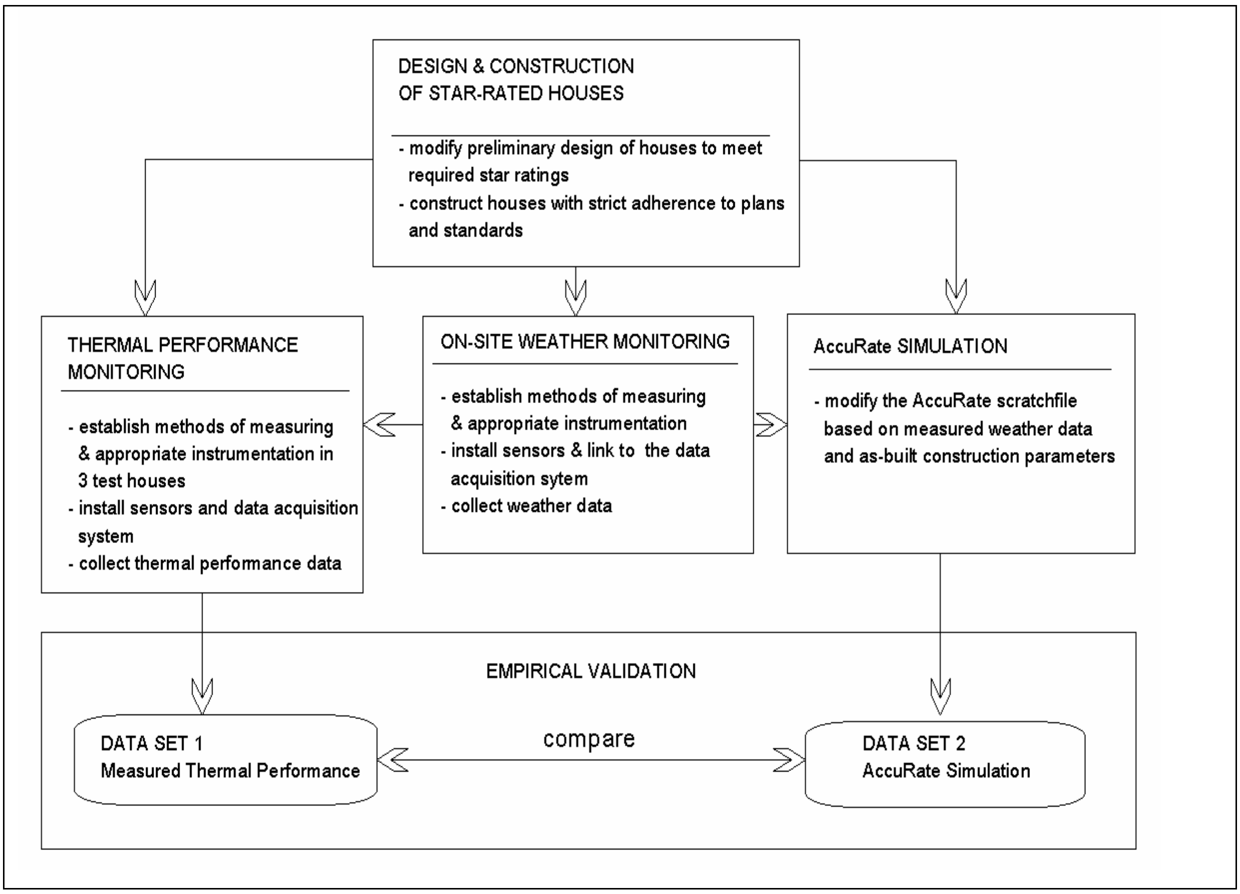


Figure 4.1: Schematic diagram of the empirical validation method used in this study

The first part of this chapter looks at the physical models, that is, the test houses, and defines the appropriate temperature that is measured inside the houses. It provides a short background of the environmental measurement profiles of the test cells in Newcastle (NSW) and Launceston, (Tasmania) Australia. This is followed by a description of the required input data for the simulations. In order to compare the thermal performance of the physical models with the thermal performance of the simulation predictions, various input data changes were necessary for a realistic representation of the houses and climate. Changes were made to construction details and AccuRate built-in input data, prior to running the simulation of the houses in a free-running operation (no heating and cooling), with the houses unoccupied. The final section concludes with a discussion of the various methods that can be used to compare the simulated and measured data for the purpose of empirical validation.

The site selection, design and construction methods of the test houses were determined by the building developer. The various star rating assessments and related building upgrade requirements of the three houses were established by the research team, in close co-operation with the building designer.

Three different star rating approaches were selected by the research team in order to be able to monitor and assess the thermal performance. These are as follows:

- A 4-star rated timber floor house, which at that time (March 2007) was the BCA's required star rating in Tasmania;
- A 5-star rated timber floor house, which at that time was the required star rating for most other states in Australia. Its performance was compared with the thermal performance of the 4-star timber floor house;
- A concrete-slab floor house having the same building fabric as the 5-star timber floor house. Its thermal performance was compared with the 5-star timber floor house.

4.2. The Physical Models

Three two bedroom houses built in Kingston (approximately 9 km south of Hobart) were the physical models for empirical validation. The availability of the houses provided the opportunity to collect environmental data, which were compared with the thermal performance predicted by AccuRate. One of the important arrangements made with the house developer was to keep the houses unoccupied for at least three months, so that data from the houses in free-running operation could be collected. The free-running operation is described as follows:

- The houses were unoccupied;
- No heating or cooling occurred within the spaces of the houses;

- No ventilation occurred via doors or windows, as all windows and doors were shut off during the monitoring period;
- No internal electrical loads such as stove, refrigerator or lights, were added to any space within the building, with the exception of the data logger in the garage;
- No internal heat loads from people or animals were added to any space of the houses while they were unoccupied.

The houses were in a controlled state and allowed to float thermally in response to changes in the external environment. Based on the AccuRate input and output requirements, the sensors and the data acquisition system were assembled to measure the external site climate parameters and the interior environment of the houses. Prior to this research project, the research team already had extensive experience with the installation of monitoring equipment for data acquisition at the Launceston test cells. Vale recommended that the same suite of monitoring equipment and installation methods be used for the test houses, in order to save time and more importantly, provide future practical validation comparisons between the test cells and the test houses (R Vale 2008, pers. comm., 28 September). Construction of the test houses started in early January 2007 and was completed at the end of June 2007. The design and construction of the houses are described in detail in Chapter 5.

4.2.1. Definition of AccuRate's Output Temperature

One of the first tasks was to determine the type of temperature to be measured in the houses. Delsante (2006) stated that the globe temperature is a good approximation of the operative temperature, which is the average of air and mean radiant temperature, weighted by convective and radiative heat transfer coefficients. (American Society of Heating Refrigerating and Air-Conditioning Engineers Inc. 2001). Delsante further advises, that the AccuRate predicted temperature are not in fact pure air temperatures, but so-called environmental temperatures, because AccuRate uses combined radiative-convective heat transfer coefficients at indoor surfaces. The globe temperature is likely to be closer to AccuRate's predicted temperature than pure air temperature.

A globe thermometer consists of a 150mm diameter hollow sphere made of copper, coated with a matt black paint, and contains a thermometer at the centre of the sphere (Hassal & Richards 1977). The globe temperature depends on the environment in which it is placed. If the walls and other surfaces which surround the globe are warmer than the air, the temperature recorded by the thermometer inside the globe will be above the air temperature because of the radiation. Conversely, when the surrounding walls and other surfaces are cooler than the air, the globe thermometer will be below air temperature. The environmental temperature can be calculated from the measured air temperature (dry bulb) and globe temperatures, and Williamson (1984) stated their relationship as:

$$T_{ei} = 6/5\ _{tg} - 1/5\ _{ta} \qquad \text{Equation 4.1}$$

where T_{ei} = environmental temperature (ºC)

T_g = globe temperature (ºC)

T_a = air dry bulb temperature (ºC)

The air temperatures and the globe temperatures in a mudbrick house in Melbourne were very similar, with differences mostly being 0.1ºC or less, and the maximum difference of 0.4ºC (Delsante 2006). It is also interesting to note that Delsante further reported that air and globe temperatures were almost identical outside the periods of extra heating, but they differed by up to 2ºC during the heated periods, with the globe temperature being the lower. The value of the globe temperature will usually be between the air and the mean radiant temperature (MRT). Melbourne's heavyweight mudbrick house was monitored in a free-running condition, and measured air temperatures were very close to globe temperatures. However, since there was no available comprehensive information on the true values of globe temperature-to-air temperature ratios in lightweight brick veneer buildings, it was deemed necessary to also measure the globe temperature in the houses (Refer also to Chapter 8.2.1 for further discussion).

4.2.2. Developing an Environmental Measurement Profile

Dewsbury (2011) reviewed and examined the methods of measuring the temperature of the PASSYS and PASSLINK test buildings in England and the test cells in Newcastle, Australia, and found these methods suitable for the test cells in Launceston. Based on historical analysis of test cell buildings in the United Kingdom, Europe and the United States, Dewsbury found it necessary to maximize the temperature data points for empirical validation projects. Figures 4.2 and 4.3 show the PASSLINK test cell building and the interior placement of sensors.

Figure 4.2: PASSLINK test building (Source: Building and Environment 43 2008)

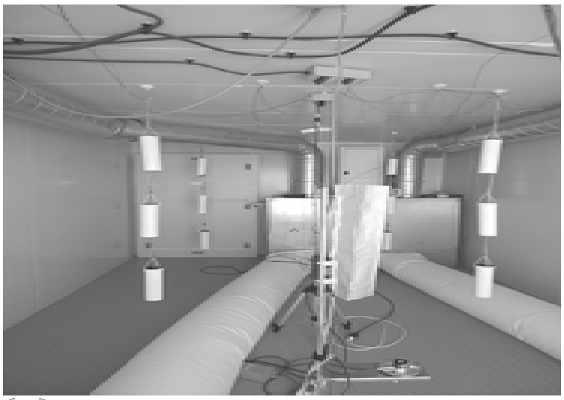


Figure 4.3: Interior of PASLINK test building (Source: Building and Environment 43 2008)

Temperature at different height levels was also considered with reference to ASHRAE Standard 55 (1992). The standard specifies the measurement of temperature at different heights as shown on Table 4.1 below.

Table 4.1: Environmental measured heights as specified by ASHRAE Standard 55

Height Above Floor	Seated Occupants	Standing Occupants
100mm	Ankle	Ankle
600mm	Waist	
1100mm	Neck	Waist
1700mm		Neck

The specific heights in Table 4.1 are based on how the average human would react to the surrounding environment. This project is not concerned with levels of comfort, but with determining average room temperatures and creating an understanding of temperature stratification within an enclosed space. Hence, temperature was measured at 600mm, 1200mm and 1800mm above floor level of the rooms.

Lomas (1991a) developed a criterion for classifying data sets for the empirical validation process and is of the view that measured building performance data and the weather data must be recorded at least hourly or at more frequent intervals if possible. Lomas further recommends that for validation purposes, single family dwellings should not be substantially modified, should be of typical construction for the local region and if possible, unoccupied. Delsante (2005b) recommended that measurements at 10 minute intervals are appropriate to calculate accurate hourly temperatures. He also suggested that the minimum requirement for the period of measurement should be at least two weeks, with at least one period during the cool months and the other during the warm months.

Prior to this study, three test cells were built in Australia by the University of Newcastle in 2004, for the purpose of measuring the effect of thermal mass in residential buildings (Sugo et al. 2006). Insights of the University of Newcastle's research team and an actual site visit in March 2007 to observe the installation of measuring equipment were very useful for this study. While the aim of the University of Newcastle's research was not to validate a simulation program, the practical knowledge of installing sensors and acquiring data was of great importance. The University of Newcastle's research team provided invaluable technical advice based on their monitoring experience, emphasized some of the problems and failures, and at the same time highlighted and recommended the successful and proven part of their research. Figures 4.4 to 4.7 show the test cells in Newcastle and some of the sensor installation details.

Figure 4.4: Three test cells at University of Newcastle (Source: Sugo 2006)

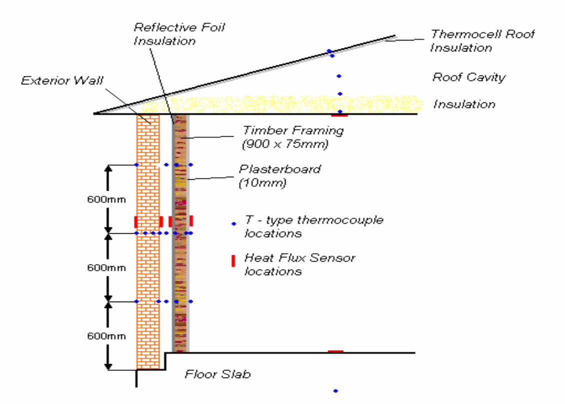


Figure 4.5: Location of thermocouples and heat flux sensors within the test cells (Source: Sugo, et al. 2006)

Figure 4.6: Internal view showing the heat flux sensor at the window, air temperature sensors at the pole, DT 600 data logger and the thermocouple isothermal box (Source: Sugo 2006)

Figure 4.7: Shielded thermocouple installation at the sliding door (Source: Sugo 2006)

The instrumentation of the three Launceston test cells (Dewsbury et al. 2007) was also carefully studied. The major concerns for the test houses were what and where to measure and this was already pre-determined by AccuRate's input requirements. As mentioned previously, an insight based on the PASSLINK project was to provide a wide range of environmental measurements to establish reliable average environmental data. Figure 4.8 shows the horizontal measuring profile of the test cells in Launceston.

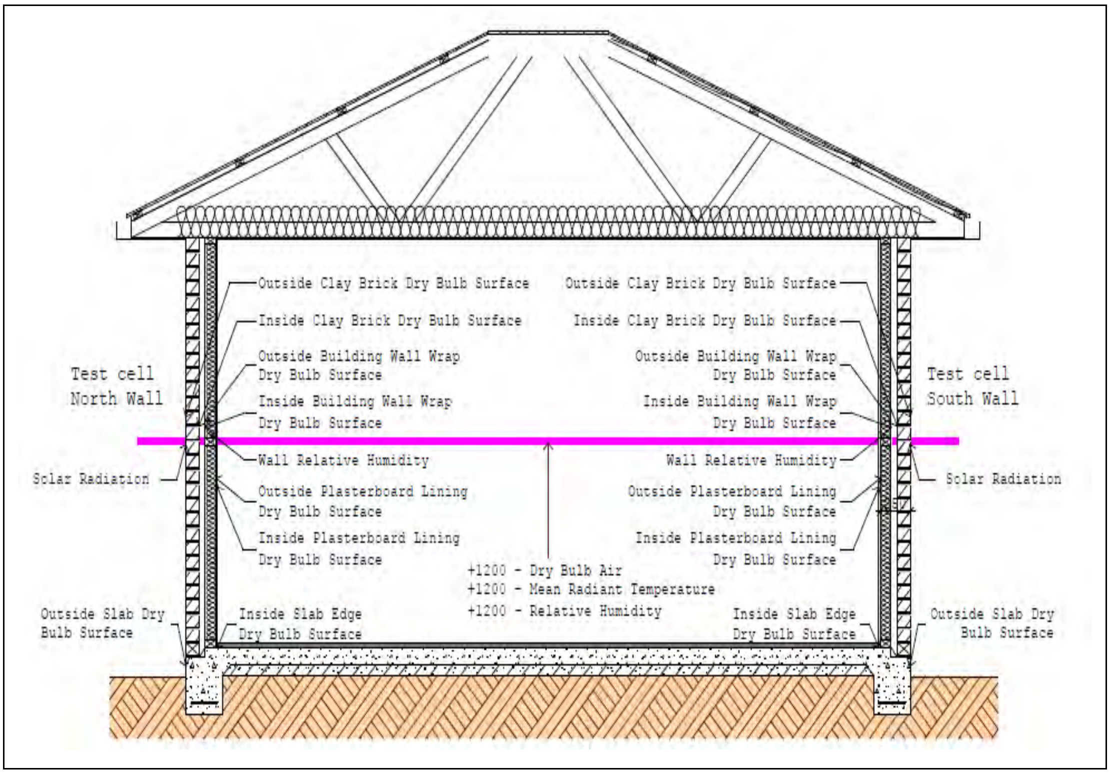


Figure 4.8: Horizontal environmental measurement profile of Launceston test cell with a concrete slab-on-ground floor (Source: Dewsbury 2007)

Measurement profiles in the test houses were based largely on the Launceston test cells. However, air speed in the subfloor and the roof space and humidity in the wall cavity were not measured in the houses.

4.3. The Simulation Program

The simulation software program for empirical validation is the HERS AccuRate. This software requires comprehensive input of project and construction data. It is important that the input data be accurate, therefore rigorous checking and verification are required. For the purpose of empirical validation two important changes and adjustment were made in the AccuRate built-in input files, called the 'scratch files', namely:

- Adjusting AccuRate's scratch files to the 'as-built' construction condition of the houses. Specifically, changes were made to: the insulation values, infiltration rates, thermal bridging of building materials within the insulated building fabric, window glazing framing ratio and adjustments, to reflect a free-running condition of the houses;

- On-site weather data were used in lieu of AccuRate's inbuilt weather data, to account for the actual external climate conditions.

It is important to note that the normal user of AccuRate is not permitted to modify AccuRate's scratch file, as this would invalidate the assessment for compliance with the BCA.

4.3.1. As Built Construction Input Data

a) Insulation

In many cases, changes to building design were executed during the construction stage and these were reflected into AccuRate input files. The most common change during the construction stage was the levels of insulation installed into the building fabric. For example, such change was necessary due to the installation of downlights, where Australian Electrical Installation Wiring Rules regulate that bulk insulation in the ceiling space must not be installed within 200mm distance of the recessed downlights and transformer (Australian/New Zealand Standard 3000 2007). With 14 recessed downlights installed in the ceiling, the insulation gap of 200mm around each recessed downlight reduced the overall value of insulation of the ceiling.

b) Infiltration

Another aspect of the as-built condition is the infiltration rate of the house. The infiltration rate represents the volume of air replaced within one hour and this differs from building to building, depending on the site condition and the sealing quality of the building's external fabric. The task of determining the infiltration rate of the houses was commissioned by the Mobile Architecture and Built Environment Laboratory (MABEL) of the School of Architecture and Building, Deakin University, Geelong. The tests were executed from 26 to 29 September 2007. Additional test details provided by MABEL are described in Chapter 7.

c) Structural Framing Ratio

The framing ratio affects the amount of thermal bridging of timber framing members, such as wall and ceiling members. AccuRate does not incorporate framing ratio calculations and uses an insulation R-value for the entire building fabric area, ignoring the area of timber framing (Belusko 2008). As the R-value of the timber members are considerably lower (R 0.53 for a 90mm timber hardwood studs compared to R 2.5 for bulk insulation), the average R-value of the building fabric is reduced, depending on the ratio of timber framing to insulation in the building fabric. Kosny et al. (2007) demonstrated that for an insulated timber framed wall structure, the lower R-value of the timber studs reduced the total insulation value of the wall by up to 30%. Dewsbury et al. (2009) modeled three houses using original and revised insulation values, based on the timber framing ratio. When the houses were modeled with AccuRate, the results showed 18% more heating load for the revised case. The New Zealand Standard 4214 (2006) recognizes the importance of framing factors and provides a calculation method to establish the true thermal resistance of a building fabric. The ASHRAE 2009 Handbook of Fundamentals covers the topic of framing ratios and illustrates both calculation methods, namely: the parallel-path method and the isothermal-planes method. For this project, the calculation of the actual framing ratio for the walls and ceiling and the effect of the insulation values of the test houses are presented in Chapter 7: AccuRate Thermal Performance Simulation of the test houses.

d) Glazing Framing Ratio

Windows and sliding doors have different glass framing ratios depending on the window design. The exact ratios of glazing and framing are important data because they affect the thermal bridging of window frames. They can be adjusted in the AccuRate's scratch file. The calculation of the window framing ratio for window and sliding glass doors is included in Chapter 7.

e) Summary of Changes to AccuRate's Input Data

AccuRate simulation results were compared with the measured data from the free-running operation of the houses. Modifications to each AccuRate input file were necessary to represent the house's actual thermal performance, as follows:

- Modification of ceiling insulation value, taking into consideration the large insulation gaps around the 14 recessed light fittings;
- Modification of air change rates of the houses using measured data on site;
- Modification of framing ratio and adjustment of the average insulation values and insulation thickness for walls and ceiling areas;
- Modification of window framing ratios;
- Modification of input files to simulate free-running operation. This included changing the input data to account for the following conditions:

  - The houses were not heated and cooled;

  - The houses were not ventilated, as all windows and doors were shut during the monitoring period;

- There were no internal heat gains as the houses were unoccupied during the free-running operation.

4.3.2. Site Weather Input Data

For the empirical validation process it was imperative to acquire on-site weather data to achieve more realistic simulations of building thermal performance. The inbuilt AccuRate climate file represents average climate conditions for many years, for a particular climate zone, collected from the nearest Bureau of Meteorology weather station. The climate file consists of twenty-seven input parameters, of which fourteen are necessary for the thermal simulation program. AccuRate's essential input data and the corresponding units are as follows:

- Month (number);
- Day (number);
- Hour (number);
- Dry bulb air temperature (tenth of degree Celsius);
- Moisture content (tenth gram per kilogram);
- Atmospheric air pressure (tenth of kilopascal);
- Wind speed (tenth of metres per second);
- Wind direction (0-16);
- Cloud cover (0-8);
- Global solar radiation (W/m^2);
- Diffuse solar radiation (W/m^2);
- Normal direct solar radiation (W/m^2);
- Solar altitude (0 to 90 degrees);
- Solar azimuth (0 to 359 degrees).

Determining AccuRate's climate inputs revealed the essential measurements necessary for the on-site weather station of the test houses. On-site weather data were collected from the test houses, and the on-site weather file was substituted for AccuRate's default climate file. The specific adjustments to the AccuRate input files, (incorporating the changes to better represent as-built construction conditions and using on-site weather data), are presented in Chapter 7: AccuRate Simulations.

4.3.3. AccuRate's Output Reports

AccuRate generates five output reports, namely:

- Temperature file;
- Energy file;
- Output mean temperature file;
- Star Rating Report;
- Building Report.

The temperature file shows the simulated hourly temperatures for each zone. AccuRate separates the zones into conditioned (heated and cooled) and non-conditioned zones. Apart from the garage, store rooms, toilets and bathrooms, the non-conditioned zones include the roof space and the subfloor area of the house. Table 4.2 shows a sample of an AccuRate temperature file data with the simulated temperature values shown to one decimal place.

Table 4.2: Sample of AccuRate's out-put data on simulated temperatures

Month	Day	Hour	Outdoor	Kitchen Dining Livin(	Bed 1	Bed 2	Bed 3	EnSuite	Laundry	Bath	Roofspace
1	1	0	17	20.9	21.1	20.3	20.6	21.3	19.9	16.5	17
1	1	1	16.4	20.7	21	20.1	20.4	21.2	19.8	16.3	16.7
1	1	2	15.8	20.4	20.8	19.9	20.2	21	19.5	15.5	16.2
1	1	3	14.9	20.1	20.5	19.6	19.8	20.8	19.2	15	15.6
1	1	4	14.3	19.8	20.2	19.3	19.5	20.5	18.8	14.5	15
1	1	5	14.6	19.8	20.1	19.1	19.4	20.4	18.8	14.9	14.6
1	1	6	15.1	20.3	20.2	19.4	20.4	20.6	19.3	16.2	14.8
1	1	7	16.3	20.7	20.4	19.8	21.3	20.5	19.5	20.9	16
1	1	8	18	21.9	20.6	20.5	21.8	20.7	20.3	26.6	18.5
1	1	9	19.7	22.9	21.2	21.9	21.6	21	21.8	33.1	22.1
1	1	10	21.4	23.1	22.4	23.3	23.5	21.6	22.3	36.8	25.9
1	1	11	22.2	23.8	23.3	24.4	24.2	22.2	23.1	37.2	28.7
1	1	12	23.8	24.8	24.3	25.6	25.4	22.8	24.3	35.4	30.2
1	1	13	24.1	25.3	24.9	26.1	25.8	23.7	24.7	40.5	31.6
1	1	14	24.5	23	25.6	26.5	26	24.2	25.1	39.9	33.3
1	1	15	23	24.7	25.5	25.6	24.9	23.5	24.1	37.6	33.4
1	1	16	21.8	23.8	24.9	24.6	23.8	22.7	23.1	32	32.2
1	1	17	20.4	22.8	23.9	23.2	22.5	21.9	21.9	26.9	29.8
1	1	18	19.2	21.9	22.6	21.8	21.3	21.1	20.8	22.2	27

AccuRate's temperature output data were used as the simulated temperatures for comparison with the measured data from the houses. The output temperature is accurate to a tenth of a degree Celsius and hence, temperatures were measured to the same degree of accuracy for this project.

The Energy file provides the energy required to maintain the conditioned zone within a pre-selected temperature range.

The Output files predict the monthly mean temperature and mean temperature ranges for all zones of the house, for each month.

The Star Rating Report represents the number of stars given to a particular house design, including heating and cooling requirements (MJ/m^2.annum). This report is generally used for the building star rating assessment for BCA compliance purposes.

The building report presents a detailed report of the construction input parameters. This report is a very useful tool for the AccuRate user, for double checking the project's input data at the completion of a simulation. The building data report summarises the building fabric's details, including specified areas and thicknesses of building materials.

4.4. AccuRate Simulations

For the purpose of determining incremental effects to the simulations of changes made to the input data, the following stages of AccuRate simulations were carried out:

4.4.1. Blind/Blind

This was the basic AccuRate simulation, based on the in-built values of the building fabric and the climate. The term Blind/Blind refers to the blind view of the building fabric (based on the physical model's building plan documentation only) and the blind view of the climate (based on AccuRate's in-built climate file for a specified climate region). This is the standard type of simulation used for the star rating reports by the house energy rating assessors.

4.4.2. Blind/Climate

This was an AccuRate simulation where the original default values for the building fabric were used, but on-site measured climate data was substituted in place of the default climate file. This simulation was carried out to identify the difference in thermal performance based on the in-built climate and the on-site measured climate data.

4.4.3. As-Built/Blind

With this type of simulation the input data values of the building fabric were on based on the 'as-built' model of the houses. Modified fabric building values were then used for the simulation. In-built (default) values for AccuRate's climate were used. In this type of simulation, the difference between 'as-designed' (building fabric information based only on building plans) and 'as-built' (building fabric information based on the observed condition) were clearly identified. This type of simulation has been used for past validation projects of thermal simulation programs.

4.4.4. As-Built/Climate

This AccuRate simulation used the 'as-built' values for the building fabric for the physical model and the on-site measured climate data. This type of simulation was used for the empirical validation of AccuRate in this research.

4.5. Methods of Analysing Validation Data

4.5.1. Review of analytical methods and techniques

The methods of comparison are very important in determining if a model is working or not. According to Jensen (1995), comparisons between measured and predicted values are often performed in a very subjective way by visually comparing graphs of measured and predicted data. While this is a simple and quick method of comparison, it is only the initial step in a validation process. Jensen also reported that the method of graphical temperature comparison can give imprecise information about what may be the cause of deviations. He recommends that statistical techniques should also be used to assess resulting uncertainties in the program output parameters and that uncertainties should be identified.

There are a number of statistical techniques for comparing measured and predicted values and testing the goodness-of-fit of different aspects of a program. In the PASSYS Model Validation and Development Subgroup, two different statistical tools were applied, namely: the parametric sensitivity analysis and the residual analysis (Lomas & Eppel 1992).

Jensen (1995) describes the analysis of the results and assessment of the sensitivity as follows:

- The parametric sensitivity analysis includes the differential sensitivity analysis and the Monte Carlo method. With the differential sensitivity analysis perturbed simulations are performed by changing each input parameter by its standard deviation. Based on the results, the overall uncertainty band of the simulation is calculated. The agreement is said to be good if the measured value fits within this uncertainty band. The advantage of this method is that it is very clear when good agreement is obtained. Parametric sensitivity analysis can only compare measurements and predictions in the low frequency range and cannot test the goodness-of-fit at other frequencies, such as the dynamic part of the experiment. Other statistical methods have been therefore developed for such procedures including the residual analysis. The residuals (the time series of the difference between measurements and predictions) are analysed in the power spectrum, and the cross-correlation function between residuals and certain input parameters of the simulation model are analysed in the time and frequency domain. The power spectrum discloses at which frequency the residuals appear and the analysis of the cross-correlation function discloses which input parameters are correlated with the residuals and therefore may cause divergence. Finally, the squared spectra are analyzed to determine how large a part of the residuals may be explained by the input parameters. While the residual analysis does not disclose what is wrong with the program, it does indicate where to look for inappropriate assumptions.

Williamson (1995, p. 268) pointed out several inadequacies in the goodness-of-fit between measured and predicted data in a variety of empirical validation projects as follows:

- ‘No attempt is made to take into account the severity of the validation test;
- None gives a single measure of success (or otherwise) of the test;
- Isolation of sources of error is difficult;
- Tests cannot be used easily for internal validation and / or algorithm “tuning’.

Williamson further describes an objective technique for establishing the accuracy of simulation predictions, called the ‘Confirmation Technique’. In this technique of analysis a confirmation factor ‘C_s’ and the degree of confirmation factor ‘D’ are established to respond to the degree of correspondence to reality; the severity of the test, and to decide if the test result is sufficient to provide confidence that the model can be used for decision-making. He concluded that a minimum acceptable program level can be established based on the degree of confirmation factor. Williamson suggests that D>0.80 would seem to ensure a program of sufficient accuracy for most design decision-making.

Table 4.3 below represents a summary of degree of confirmation analysis and the goodness-of-fit statistic for a 7-day comparison of measured and predicted environmental temperatures in the living area of the CSIRO’s experimental low energy consumption houses (LECH) in Highett, Melbourne (Williamson 1995). The simulations were performed with the program EnCom 2.

Table 4.3: Degree of confirmation D and goodness -of-fit statistics (Source: Williamson 1995)

	ξ_1	ξ_2	ξ_3	ξ_4	Average
Confirmation Factor C_s	0.892	0.679	0.188	0.865	0.656
Degree D	0.970	0.962	0.875	0.970	0.944
Confirmation Factor C'_s	0.379	0.751	0.469	0.509	0.526
Degree D'	0.800	0.888	0.832	0.843	0.841

Table 5: Degree of Confrimation D' *EnCom2* Results

	ξ1	ξ2	ξ3	ξ4	Average
Degree D'	0.835	0.900	0.867	0.873	0.870

While there are a number of methods of analysing validation accuracy, the statistical method of identifying the residuals between measured predicted values should be the basis of any empirical validation process. However, predetermining a particular expected accuracy of a program and setting the parameter for passing or failing the test is more intricate. Establishing a confirmation factor ‘D’ and providing a single measurement of success of the test would also provide concrete answers regarding the accuracy of the program for its use as an acceptable design tool.

4.5.2. Methods of Analysing Validation Data used in this Study

Two sets of data, the simulated and the measured data, were compared and analysed. Both data sets provided hourly time steps between the values. The primary objectives of the validation analysis were as follows:

- To demonstrate a relatively straightforward method of comparing the data sets;
- To present an analysis that could provide a basis for further developing and improving the software.

The first objective was achieved by using linear graphical temperature diagrams utilizing the graphical function within the spreadsheet based software EXCEL. General temperature profiles and differences in minimum and maximum temperatures between simulated and measured values in the zones of the houses were presented for each of the houses. The second objective required statistical analyses, specifically: linear correlation and residual analysis. These two options are discussed below.

a) Graphical Analysis

Linear graphical analysis was undertaken to visually compare simulated and measured hourly temperature values. This type of analysis allowed for a convenient visual comparison of temperatures between 5 September 2007 and 26 September 2007. An analysis of the differences between simulated and measured maximum and minimum temperature was undertaken. This method was used to initially identify key temperature trends in the zones of the houses. If temperature profiles of simulated and measured temperatures were very similar, the software simulation was correct. If the temperature profiles were similar, with corresponding trends of peaks and troughs but indicating different values, this may indicate faulty sensor calibration or suggest that aspects of the software needed improvement. If the temperature profiles were dissimilar, the software may have been inappropriately considering climate conditions or aspects of the building fabric. Figure 4.9 shows the graphical comparison of simulated and measured data for one of the test cells in Launceston for one week in July 2007 (Dewsbury et al. 2009).

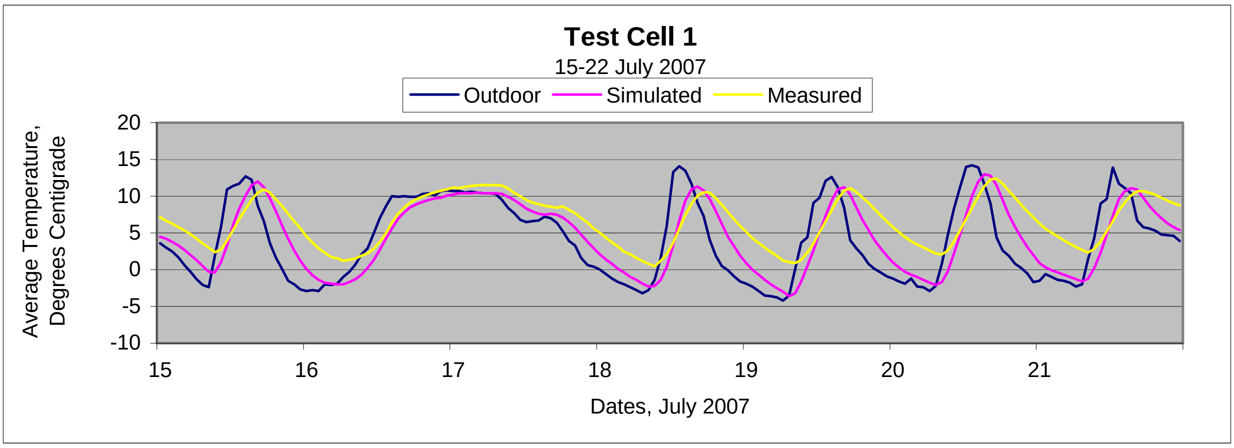


Figure 4.9: Outdoor, simulated and measured temperatures in test sell 1 during a cold week (Source: Dewsbury 2009)

The graphical analysis shows the temperature profile comparison of the simulated and measured temperatures and the simulated and measured maximum and minimum daily temperatures comparison of the houses. Figure 4.9 shows that the maximum simulated and measured temperatures are very similar, however minimum temperature comparison is dissimilar, showing up to 3ºC lower simulated temperatures, when compared to the measured temperatures.

b) Statistical Analysis

The statistical analysis was undertaken to provide an indication of the accuracy of the simulation and to offer an explanation for the simulation errors, especially in relation to the modeling by the software. The statistical analysis included the following examinations:

- Correlation between measured and simulated temperatures;
- Distribution of residuals;
- Correlation of residuals between adjacent zones;
- Correlation of residuals zones and climate parameter.

4.5.3. Correlation between measured and simulated temperatures

To examine how different the simulated and measured temperature values are, correlation analysis was used. This technique determines the extent to which changes in the value of the simulated temperature are associated with changes in the measured temperatures. As a rating tool, the AccuRate software should predict temperatures as closely as possible to measured temperatures at any time, and an increase in measured temperature should correspond to a proportionate increase in simulated temperature. The proximity of the simulated temperature to the measured temperature is examined by drawing the scatter plot, with the measured temperature in the X-axis and the simulated temperature in the Y-axis. If the line of best fit to the scatterplot slopes upwards (positive slope) and its correlation factor is close to 1, this indicates that the AccuRate simulation is directly correlated to the measured temperature in a linear manner, and their values are very close. For a perfect fit line, the correlation factor is 1. This means that the measured and simulated temperatures are equal. If the line of best fit slopes downward (negative slope), this indicates that the simulated program has a potentially serious problem that needs to be further examined. The tighter and more concentrated the data is accumulated around the trend line, the greater is the correlation within this cluster of data.

All scatterplots display a correlation factor 'r' at the lower left hand side of the diagrams. The correlation coefficient is an indication of the strength of linear association between the variables. For the purpose of identifying the strength of correlation, the value r can be classified as follows: (F Soriano 2010, pers. comm., 21 December).

- > 0.8 indicates a high degree of correlation;
- 0.5 to 0.8 indicates a moderate degree of correlation;
- < 0.5 indicates a low degree of correlation.

Two lines are shown in the diagrams, namely, the best fit line (a black continuous line), and the perfect fit line (a red dotted line). By comparing the two lines, it is possible to examine how closely the program is predicting the simulation to reality throughout the temperature range.

4.5.4. Residual Analysis

The residual temperatures, referred to as 'residuals', are the actual temperature errors of the simulation. The residuals' values are obtained by subtracting the simulated temperature from the measured temperature, as shown in Equation 4.2.

$$\text{Residual Temperature} = T_m - T_s \qquad \text{Equation 4.2}$$

where T_m = Measured Temperature

T_s = Simulated Temperature

a) Residual Histogram

This part of the residual analysis employs the histogram to examine the range, frequency, and distribution of residuals. One observation represents the value of mean hourly temperature data. This method also examines the normality of distribution of grouped residuals (or errors), and clearly shows the frequency of positive and negative residuals. A positive residual value indicates that the simulation under-predicted the temperature, whereas a negative residual value indicates that the software over-predicted the temperature.

To investigate the cause of the difference between the simulated temperature and the measured temperature, correlation analysis is used as follows:

b) Correlation of residuals between adjacent zones.

This analysis investigates the correlation of residuals between adjacent zones of the house, as a means of examining how the residual values or simulation error in one zone may impact residual values or simulation error of an adjacent zone. The software program calculates temperatures based on an energy balance equation in the house considering many factors such as: fabric conductivity, material emittance values, thermal capacitance and external climate inputs. If the software has not correctly calculated the thermal performance of one zone, this would also affect the thermal performance of the adjoining zones. For example, when the residual value for one zone has a positive value, (that is, the software under-predicts the temperature), this can be due to the software modeling too much heat to adjoining zones with less heat or energy level remaining in the original zone. Scatterplots are drawn with the residuals of one zone in the X-axis and the residuals of an adjacent zone in the Y-axis.

c) Correlation of zone residuals and climate parameters.

This part of residual analysis focuses on the examination of zone residuals with the measured climate parameter, namely: external air temperature, global solar radiation, wind speed and wind direction. One of the major factors affecting the thermal performance of buildings is the external climate. The use of measured site climate data in the simulation is one of the fundamental necessities in the empirical validation process.

4.6. Summary

The research methods used in this study were linked closely to two previous case studies, namely those employing heavy weight test cells in Newcastle, NSW and the light weight test cells in Launceston, Tasmania.

Extensive modification of AccuRate's input data ensured the simulations were based on realistic data, including changes to the houses' 'as-built' building fabric and the use of site-measured climate data.

The empirical validation analysis employed linear graphical temperature diagrams and detailed statistical analysis. While the graphical analysis allowed a quick visual comparison of the two variables, the statistical analysis allowed for a much deeper understanding of the relationship between: the simulated and measured values, the correlation of residual of the adjacent zones of the houses and the correlation of the zones residuals and climate parameters. The information provided by the graphical and statistical analysis provided a satisfactory method of understanding the complex and large volumes of data analysed for this research project.

Chapter 5 describes the design and construction of the test houses in Kingston, Tasmania.

Chapter 5: Design and Construction of the Test Houses

5.1. Introduction

Chapter 4 outlined the research design for this project and concluded that the empirical validation will be based on linear graphical analysis and detailed statistical analysis.

This chapter describes the design and construction of the three test houses and the construction solutions to achieve the desired star rating of each of the houses.

Before commencing the construction of the proposed houses by the developer Wilson Homes, a thermal assessment was undertaken, using AccuRate to determine the star rating of the building fabric for the three test houses from the building plans to the following requirements:

- An enclosed platform timber floor house with a 4.0-star rating requirement;
- An enclosed platform timber floor house with a 5.0-star rating requirement;
- The same house as the enclosed platform timber floor house but constructed with a concrete slab-on-ground floor, in lieu of the timber floor.

Construction started in March 2007 and was completed in early July 2007. The monitoring of the free-running stage of the houses (unoccupied and unconditioned) started on 5 July 2007 and concluded on 29 September, 2007.

5.2. Determining the Star Rating Requirements of the Test Houses

As the test houses are relatively small (85.70m²) compared to the average size of the Australian home (215m² in 2007), the houses were based on the "calculated energy requirements" and not based on the "area-adjusted energy requirement". The star rating benefit for the small test houses would have been 0.9 of a star when compared to 200m² sized houses.

The housing developer, Wilson Homes, supplied the researcher with a completed set of architectural working drawings, namely:

- Site plan, scale 1:250;
- Floor plan, scale 1:100;
- Elevations, scale 1:100;
- Section, scale 1:50;
- Floor structure layout plan, scale 1:100;

- Bracing plan, scale 1:100;
- Energy efficient plan, scale 1:100;
- Electrical plan, scale 1:100.

The developer provided a set of drawings and specifications based on the 'Deemed-To-Satisfy' approach (DTS) in which the building fabric specifications were selected directly from the BCA to achieve 4.0 stars. The initial building plans were simulated using AccuRate and achieved a star-rating of 3.6, hence further AccuRate assessments were required to obtain the required star rating of 4 for this project. After various discussions with the School of Architecture and Design, the developer decided on the following upgrades to achieve the 4 star rating of the enclosed timber platform floor:

- Providing guards over the recessed light fittings to change AccuRate settings from vented to un-vented down lights, resulting in a 0.3 star rating improvement;
- Insulating the bedroom and bathroom wall facing the garage with R 1.5 fibre glass insulation, resulting in a 0.1 star rating improvement;
- Choosing a black roof colour, resulting in a 0.05 improvement of star rating.

To further improve the star-rating from the 4-star enclosed timber platform house to the required 5-star rating of the timber floor house the following further improvements of the building fabric were carried out:

- Upgrade the ceiling insulation from R3.5 to R4.0, resulting in a 0.1 star rating improvement;
- Increase the exterior wall insulation and the interior wall insulation facing the garage from R1.5 to R2.5, gaining 0.2 stars;
- Double-glaze windows and sliding doors in the kitchen dining living area, resulting in a star rating improvement of 0.7 stars.

There were numerous discussions regarding the different choices available to achieve the star rating requirements but the final decision was left to the developer. While most of the star rating improvement choices were based on financial consideration, the preference to double-glaze the kitchen/dining/living area of the house, rather than to insulate under the timber floor, was based on practicality: while both of the methods would have achieved approximately the same star rating improvement, in this case the more expensive selection of double-glazing in the living areas was chosen. One reason for this choice was the lack of knowledge by the building industry regarding the insulation of timber floors without creating condensation problems. The floors in all three houses were covered with carpet and underlay, except in the bathroom and kitchen, where tiles were used.

Finally, the 5-star timber floor house was assessed using a 100mm concrete slab in lieu of the enclosed timber platform construction, further improving the star rating by 0.5 of a star. It is worthwhile to note that if tiles had been installed in lieu of carpet in the kitchen/dining/living area, it would have resulted in a further star rating improvements as follows:

- Light coloured tiles, 0.1 stars;
- Medium coloured tiles, 0.3 stars;
- Dark coloured tiles, 0.4 stars.

The summary of star rating requirements is presented in Table 5.1 below showing the three house types, star ratings and predicted annual heating and cooling energy requirements for each house type.

Table 5.1: Comparison of the star rating fabric requirements for the three test houses

Comparison of star-rating for the 4-star and-star and 5-star timber floor house and the concrete-slab floor house for climate zone 26 (Hobart Tasmania)			
Item	4.0-Star Timber Floor House 258.9 MJ/m²a	5.0-Star Timber Floor House 202 MJ/m²a	Concrete-Slab-Floor House 175MJ/m²a (5.5 Stars)
Recessed down lights	non-vented	non-vented	non-vented
Colorbond roof colour	black	black	black
Ceiling insulation	R 3.5 fibreglass	R 4.0 fibreglass	R 4.0 fibreglass
Exterior wall insulation	R 1.5 fibreglass	R 2.5 rockwool	R 2.5 rockwool
Interior wall insulation	R 1.5 fibreglass to garage wall	R 2.5 rockwool to garage wall	R 2.5 rockwool to garage wall
Windows and sliding doors	5mm single-glazed, sliding, aluminium-framed	5mm double-glazed, only to kitchen/dining/living area, awning windows, (12mm air gap between glazing) aluminium-framed	5mm double-glazed, only to kitchen/dining/living area, awning windows, (12mm air gap between glazing) aluminium-framed
Exterior foil wrapping	Reflective to inside of wall, taped	Reflective to inside of wall, taped	Reflective to inside of wall, taped
Floor type	Timber platform 19mm particle board	Timber platform 19mm particle board	100mm concrete-slab-on ground/fill

5.3. The Building Site and the Climate

The building site is located at 76 Auburn Road at Kingston, 9km south of Hobart. The site was a 2616 m² block with an old weatherboard house located at the front, facing Auburn Road. The old house was demolished and six 2-bedroom houses were designed for this site with three of the houses used for this research.

The site slopes about 1:14 upwards from the Auburn Road, with the long axis of about 99m facing north-west with a distant view to Mount Wellington. The photos in Figure 5.1 and 5.2 (below) show the building site before construction of the houses.

Figure 5.1: Top view of the building site toward Auburn Road

Figure 5.2: View up the building site from Auburn Road

The six two bedroom houses were situated on this building site with the three test houses placed at the north-west facing long axis. The three test houses are specified on the site plan as Unit 1, the 5-star slab floor house; Unit 2, the 5-star timber floor house; and Unit 3, the 4-star timber floor house. Figure 5.3 (below) shows the site layout and Figure 5.4 the aerial view of the housing development in Auburn Road, Kingston.

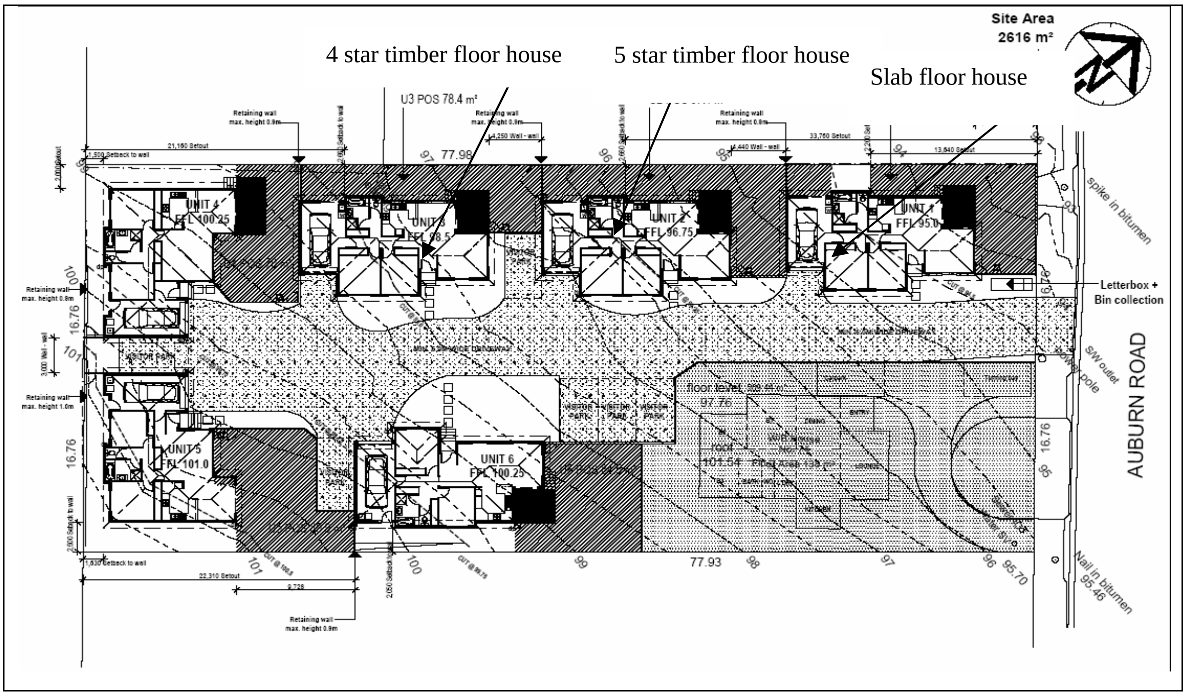


Figure 5.3: The building layout at Auburn Road Kingston (Source: Wilson Homes)

Figure 5.4: Aerial view of the completed housing development with the test houses on the left-hand side of the driveway (Source: Google Earth)

The difference in finished floor level height between each test house is 1.75m, with the concrete slab house situated at the lowest level and the 4-star timber floor house at the highest level. There is a small fenced private outdoor area dedicated for each house. A large proportion of the site is used for the grey coloured concrete driveway and designated car spaces. The site (except the section facing Auburn Road), is surrounded by other weatherboard houses on large sized blocks of land.

The climate of Kingston is very similar to that of Hobart, with cool to cold winters and mild to warm summers. Average winter temperature can range from 4ºC to 12ºC, while average summer temperature range from 12ºC to 22ºC. The dominant wind direction is from the north-west with the summer sea breezes occurring mostly from the south-east.
Tasmania’s climate is defined in the BCA’s climate zone map as zone 7 (cool temperate) with an average 3 p.m. January water vapor pressure of less the 2.1kPa, an average maximum January temperature of less than 30ºC and average annual heating degree days of more then 2000.
The climate of Kingston falls well within the parameters of the description of a cool temperate climate. There was a weather station operating in Kingston between 1910 and 1977 (elevation 55m) and some of the weather data are presented in the following Table 5.2.

Table 5.2: Kingston climate data (Source BOM)

Statistics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Years	
Temperature															
Mean maximum temperature (°C)	21.6	21.9	20.4	18.3	15.0	12.7	12.5	13.1	14.8	16.8	17.6	19.8	17.0	10	1965 1976
Mean minimum temperature (°C)	9.7	10.7	9.0	7.0	4.6	2.4	2.4	2.9	4.4	5.2	7.3	8.8	6.2	10	1965 1976
Rainfall															
Mean rainfall (mm)	46.4	46.1	52.1	57.5	55.3	58.5	56.3	55.6	51.3	68.0	61.8	65.4	674.3	64	1910 1977
Decile 5 (median) rainfall (mm)	37.6	37.8	38.3	52.3	42.8	45.0	52.4	44.6	42.9	60.1	55.2	51.2	663.0	64	1910 1977
Mean number of days of rain ≥ 1 mm	5.5	5.4	6.6	7.2	8.0	8.1	8.3	9.3	8.0	9.5	8.6	7.4	91.9	63	1910 1977
Other daily elements															

At the present the nearest weather station is situated at Ellerslie Road, Hobart with an elevation of 52m, at a distance of about 8.6 km from the test houses building site in Kingston.

5.4. The Proposed Layout of the Floor Plan

Each of the three test houses contains: 2 bedrooms, an open plan, kitchen, dining and living area, a bathroom with separate toilet and a single garage, and an internal hallway connecting bedrooms, garage and bathroom to the common living areas. The total floor area of each house is 85.70m² with an open kitchen, dining and living area of 37.30m² and a single garage and laundry of 23.86m². The open living area is situated at the north-west side of the houses and has access to a small timber deck with an area of 9.36m². There is a relatively large 13.72m² north-east facing glazed area in the kitchen/dining/living area, with a floor area of 37.30m², resulting in a window to floor area ratio of 0.36. All three test houses have an identical floor plan layout and the same floor area. Figure 5.5 shows the floor plan layout of the houses.

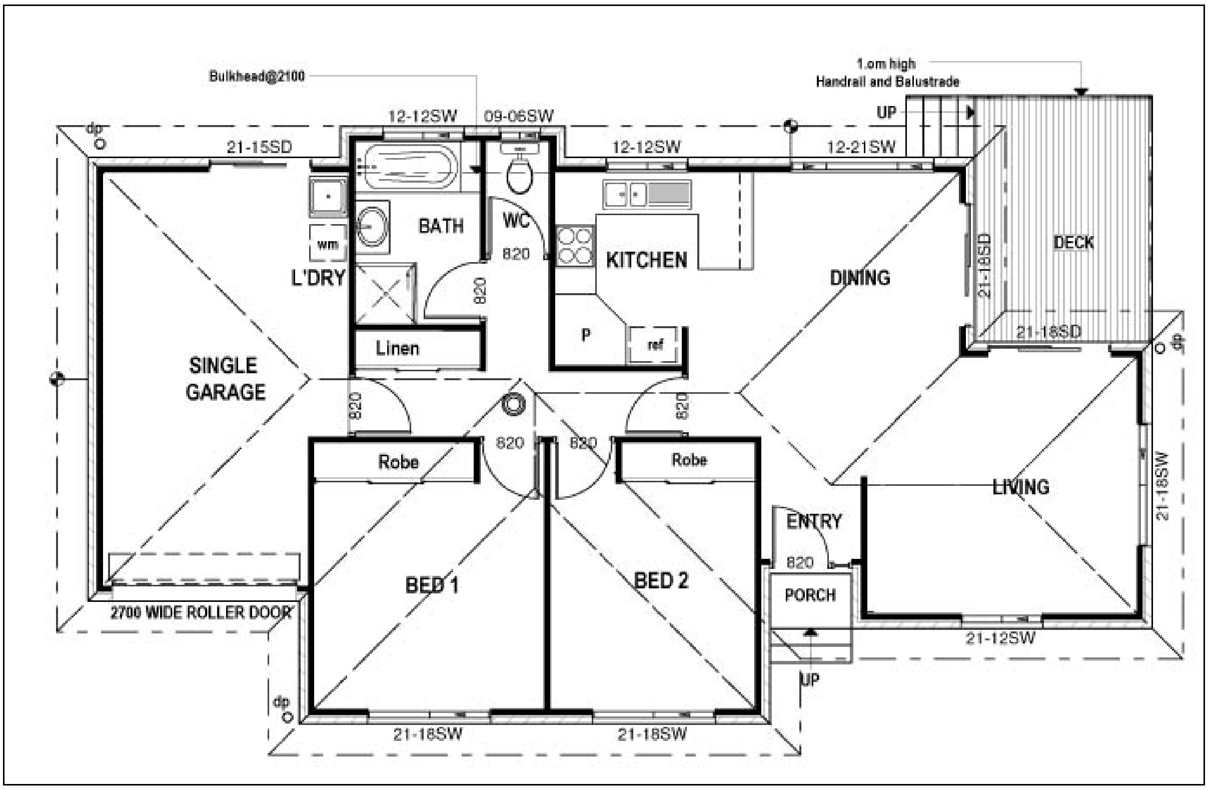


Figure 5.5: Floor plan layout of the test houses (Source: Wilson Houses)

Section 5.5 describes the construction details of the houses.

5.5. The Floor Construction

The comparison of the thermal performance of a timber floor to a concrete slab-on-ground floor has been examined by many researchers in different climatic conditions but constitutes a contested area as to which is the more appropriate floor for a particular climate zone in Australia. Walsh et al. (1982) reported that a concrete slab-on-ground construction always reduces heating requirements in comparison to suspended timber floor construction, regardless of climate severity. Conversely, Brinkly (2006) in his report titled ‘Thermal mass does it really save energy’, stated that constantly occupied buildings benefit from thermal mass, whilst intermittently occupied buildings are better constructed as light weight structures with a quick heat-up response.

Comparing the star rating simulation by AccuRate between the two flooring systems, the slab on-ground floor usually achieves a higher star rating in most of Australia’s climate zones, with exceptions in the hot tropical zone (Energy Partners 2006). Both flooring systems were therefore chosen for the 5-Star Thermal Performance Project, to compare their thermal performance, and to investigate whether or not AccuRate's higher concrete slab floor star rating prediction is justified. Figure 5.6 and 5.7 show the construction of the platform timber floor at the test houses.

Figure 5.6: Timber bearers and floor joist construction detail

Figure 5.7: Timber particleboard platform and enclosed subfloor construction detail

The enclosed timber platform construction at the test houses consist of a brick subfloor perimeter wall, with individual brick piers on concrete pads supporting the timber bearers and floor joists. Compressed particleboard flooring panels were fixed to the floor joists and provide the platform for this floor. There was no insulation installed under the timber floors in the 4 and 5-star timber floor houses. The timber floor construction is a popular building system and usually the least expensive for steep or sloping sides and for split level construction. The following Figure 5.8 depicts the timber floor construction detail at the perimeter wall of the 4 and 5-star test houses.

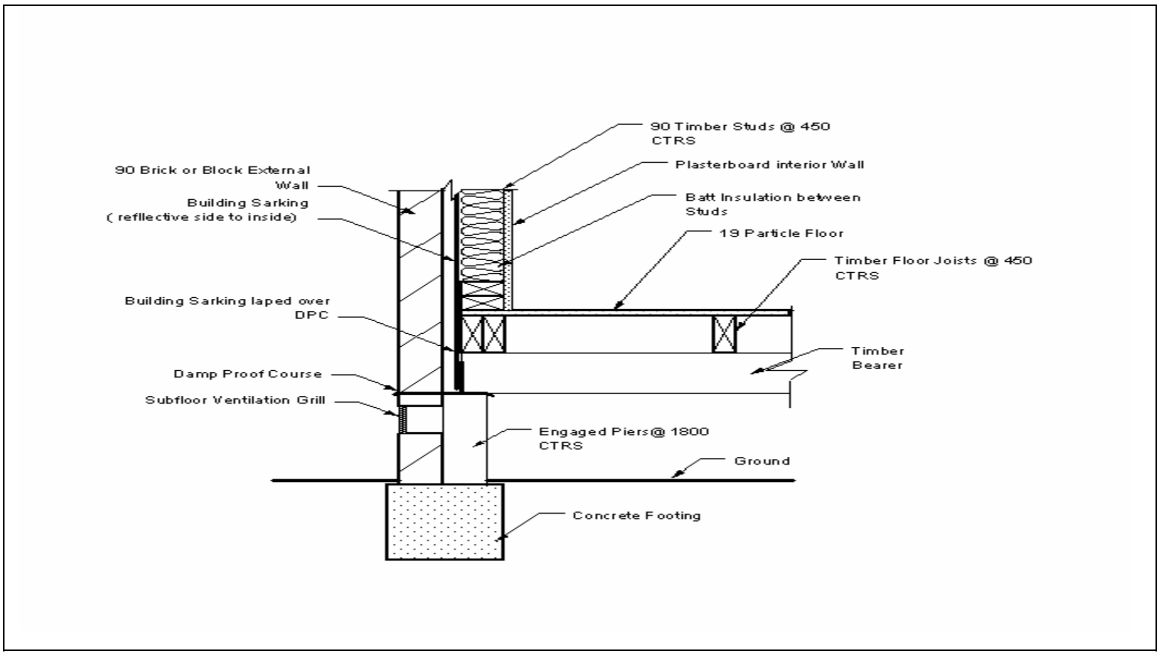


Figure 5.8: Enclosed timber platform construction detail at the 4 and 5-star test houses

Figure 5.9 shows the section drawing of the test houses with the timber floor construction, particularly illustrating the location and spacing of concrete pad footings and brick piers. The floor construction in the garage and laundry is a concrete slab-on-ground floor.

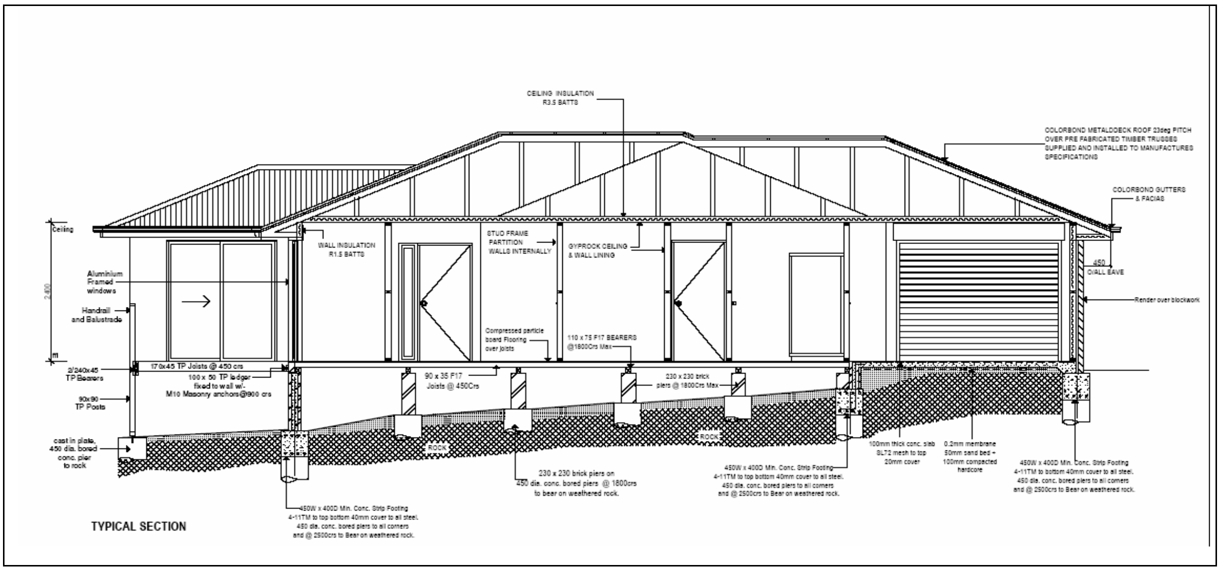


Figure 5.9: Section drawing of the timber floored test house (Source: Wilson Homes)

The concrete slab-on-ground house has a 100mm reinforced concrete slab as the main floor material. The concrete slab is positioned on a perimeter brick foundation wall, (also acting as retaining wall for the fill material) and has 400 mm deep internal concrete beams. Due to the slope of the land, the perimeter foundation wall was built to a height of about 1.2m at the front of the house and then filled and consolidated with fine crushed rock. Figure 5.10 and 5.11 show the slab house floor construction before and after the pouring of the concrete slab.

Figure 5.10: Fill preparations for the slab house before pouring of the concrete floor

Figure 5.11: The concrete slab floor after pouring of concrete floor

The slab-on-ground floor construction is the more widespread system in Australia and the least expensive construction method on level building sites. Figure 5.12 below shows the construction detail of the perimeter foundation wall of the slab floor test house.

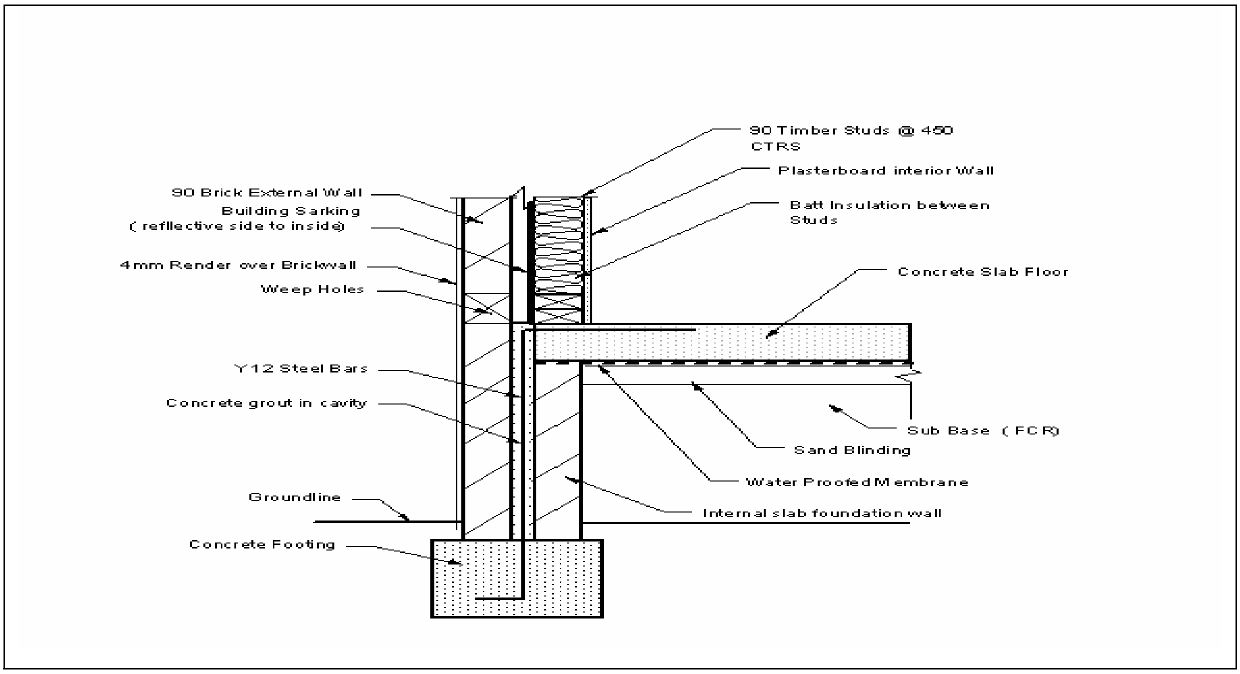


Figure 5.12: Construction detail of the slab floor test house depicting the perimeter wall detail

The timber and the slab floors were covered with carpet, except in the kitchen and bathrooms which were tiled.

5.6. Exterior Wall Construction

The brick veneer wall is the most common residential wall system in Australia and was therefore chosen for the exterior walls of the test houses. The brick veneer at the test houses consists of: a 90mm external rendered brick wall, a 35-40mm air cavity, a 90mm interior timber wall framed with studs, (usually at 450mm centres) with 10mm plasterboard sheeting fixed to the inside of the stud wall. Building sarking (a one-sided reflective foil wrapping) was attached to the exterior side of the stud wall with the reflective side facing the inside of wall. The sarking acts as the water-proofing membrane of the building section and also assists to reduce the infiltration losses of the house. Figure 5.13 (below) illustrates the typical section detail through the brick veneer wall at the test houses.

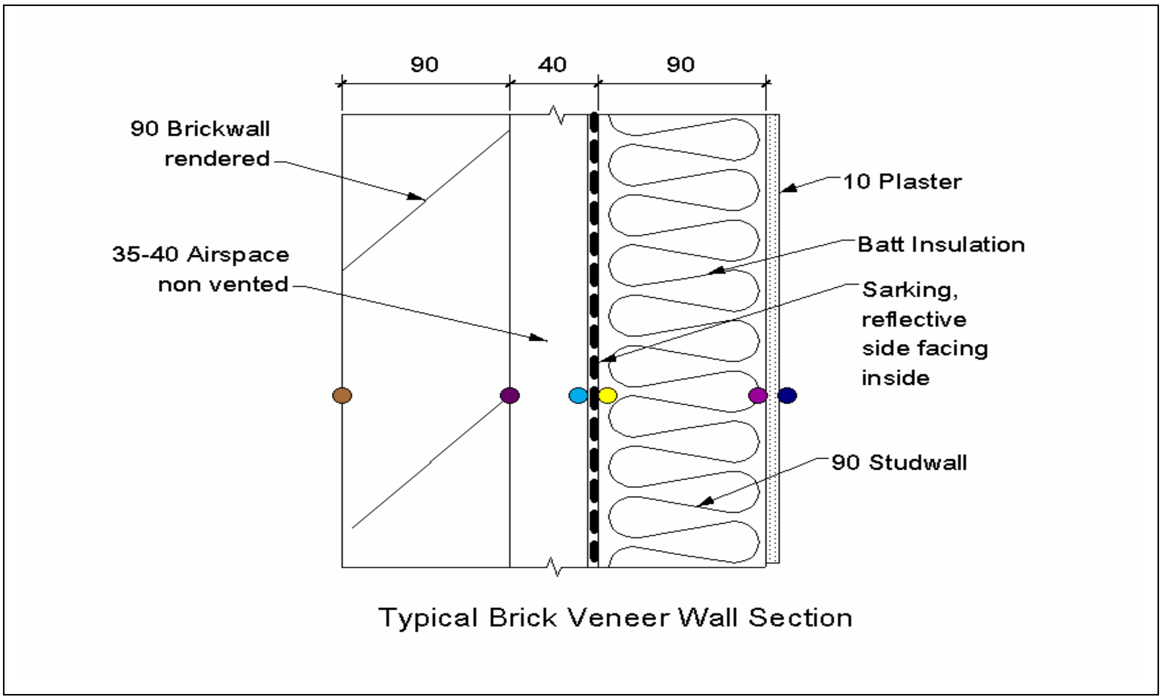


Figure 5.13: Section detail of the brick veneer wall at the test houses

Standard building practice requires a 150mm overlap of the sarking between the sheets. To reduce air infiltration and display best construction practice, the sarking at the test houses was taped at the joints of overlapping sheets and also taped around windows and sliding door frames, as well as to the top and bottom plates of the timber wall framing. Figure 5.14 and 5.15 show the taping of the sarking to the damp-proof course sheeting, consequently eliminating the air flow from the subfloor space into the wall cavity.

Figure 5.14: Taping of sarking to the damp-proof course sheeting

Figure 5.15: Installation of the sarking. Notice the overlapping and taping to the damp-proof course sheeting

Faulty and shoddy installation of sarking is a common problem in the building industry, resulting in increased air infiltration and higher air change rates (Luther 2008). It is of great importance that the building sarking be properly installed, overlapped and taped to the plastic damp course proof sheeting. Failure to do this will result in airflow between the subfloor and the cavity of the brick veneer wall and will reduce the overall insulation value of the wall system. Wall insulation was installed between the studwork of the wall. It was 88mm thick R2.5 rock-wool in the 5-star timber floor house and in the slab floor house and 75mm R1.5 fibreglass insulation in the 4-star timber floor house. Figure 5.16 and 5.17 show the installation of the wall insulation to slab-on-ground house walls.

Figure 5.16: Installation of the wall insulation

Figure 5.17: Shoddy installation of wall insulation (this was rectified later)

The detail of the eave construction has been another discussion subject by the research team. A typical eave construction detail is shown in Figure 5.18, with the eave lining installed flush to the outdoor brick wall. This is a construction detail published in the BCA's section 3.7 and is the common eave detail used by most builders in Australia. However, with this construction, the cavity of the brick veneer wall is left open to the roof space. Alternative eave construction details show the eave lining extending to the interior stud wall and sealing the cavity to the roof space, providing an unventilated brick cavity wall. It was decided to follow normal building practice and so the eave construction detail was left up to the building company. Consequently, the test houses' eave linings are constructed as shown in Figure 5.18, with the eave lining being constructed flush to the exterior brick wall. This construction detail allows direct air contact between the cavity of the brick veneer wall and the roof space and results in reduced thermal performance, particularly during the heating season.

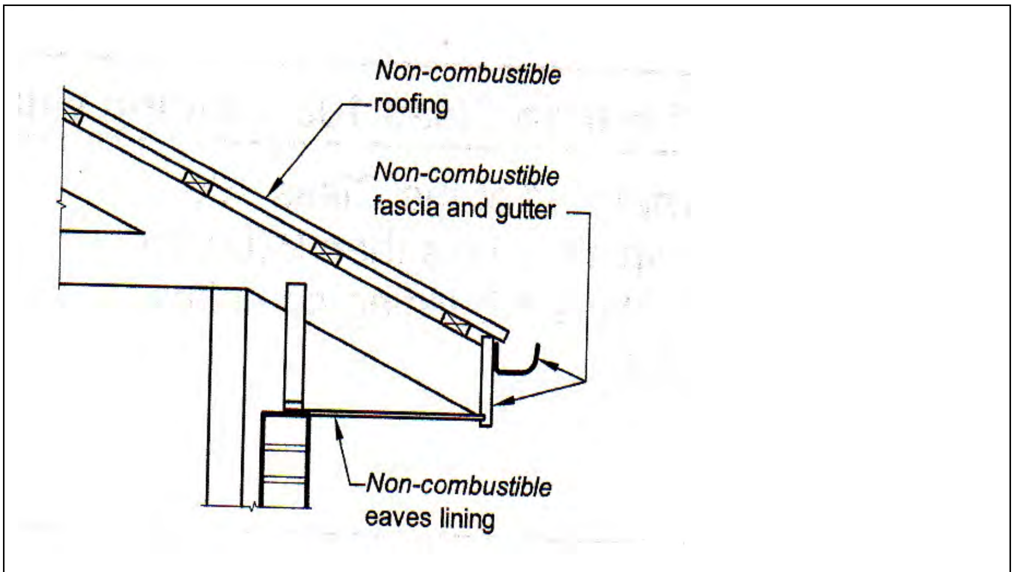


Figure 5.18: BCA eaves construction detail with an open cavity to the roof space (Source: BCA 2009 Volume 2)

5.7. Aluminium Windows and Sliding Doors

All external sliding doors and windows were manufactured by Brednams and supplied by Clark Windows, Smithton, Tasmania. Figure 5.19 shows the living room awning window at the concrete slab floor house and Figure 5.20 depicts the window certification of the window at the same house.

Figure 5.19: Awning window frame detail of the test house with concrete slab

Figure 5.20: Awning window frame detail of the test house with concrete slab

The 4-star timber house has aluminium-framed 5mm single-glazed sliding windows and sliding door, while in the 5-star timber floor house and the concrete slab house the awning windows and sliding doors in the kitchen/dining/living area are aluminium-framed, 5mm double-glazed. The double-glazed units have an internal air gap of 12mm. The double-glazed aluminium frames have no internal thermal break. The remaining windows and sliding doors in the 5-star timber floor and the concrete slab house are single-glazed. Figure 5.21 illustrates the elevation drawing of the test houses showing the placement of the windows and sliding doors.

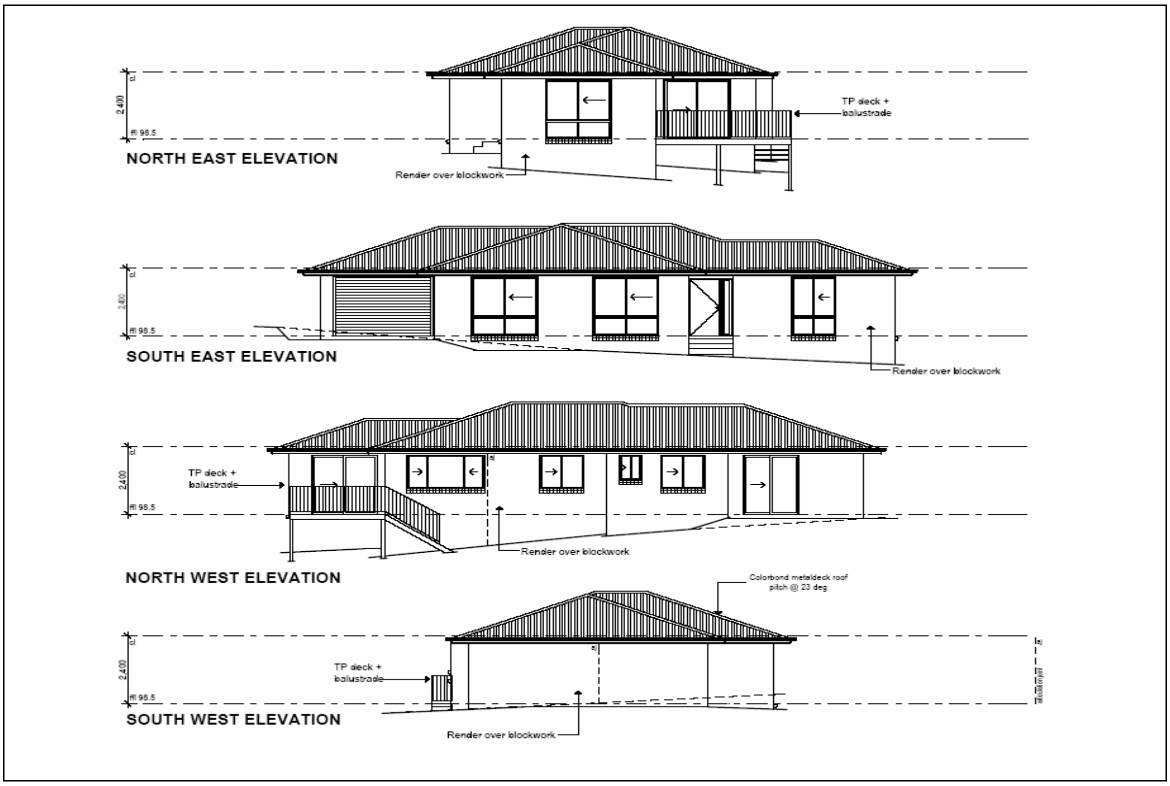


Figure 5.21: Elevations drawings of the test houses and placement of windows and sliding doors (Source: Wilson Houses)

The total area of the sliding doors and windows is 27.4m², representing 25% of the total floor area of the house. The individual window and sliding glazed areas as follows:

- To the north east wall 3.78m² (18% of north east wall area);
- To the north west wall 13.5m² (36% of north west wall area);
- To the south east wall 10.1m² (27% if south east wall area);
- To the south west wall 0m².

5.8. The Subfloor Construction of the Timber Floor Test Houses

The test houses' perimeter wall of the enclosed subfloor consists of a single brick wall with engaged piers at 1.8m intervals linked into the sub-floor wall, providing part of the load bearing foundation for the subfloor bearers. One important aspect of the subfloor construction is the provision of subfloor ventilation. The BCA determines that for climate zone 7 (Tasmania), the minimum area of subfloor ventilation should be 6000mm² per linear metre of subfloor wall, where the subfloor ground is not covered with an impervious membrane (Australian Building Codes Board 2010). The BCA's subfloor regulation provides no further reference to the actual height of the subfloor wall, or any reference to the actual volume of subfloor space to be ventilated. In the AccuRate program the subfloor is designated as a zone and provides individual simulation results for this area. Figure 5.22 shows the subfloor area under the timber floor test houses; Figures 5.23 to 5.25 show the ventilation grille installed into the subfloor perimeter wall of the test houses.

Figure 5.22: View of the subfloor of the timber floor houses

Figure 5.23: Interior view of the ventilation grille from the subfloor

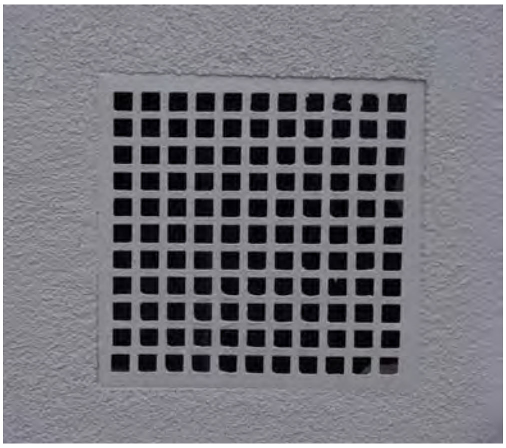


Figure 5.24: Ventilation grille installed to the brick perimeter foundation wall

Figure 5.25: Ventilation grille detail of the rendered perimeter foundation wall

5.9. Ceiling and Roof Construction

The ceiling/roof construction consists of pre-fabricated 23^{o} pitch timber roof trusses fixed to the stud wall's top-plate at an interval of 900mm. Timber roof battens are attached to the trusses, and a reflective roof sarking membrane is dished over the roof battens, with the reflective side facing downwards to the interior of the roof space. The Colorbond steel roof is fastened to the timber battens with specially designed roofing screws. Steel furring channels are fixed to the underside of the ceiling trusses with the 10mm plaster board ceiling lining attached to the furring channels. In the AccuRate simulation, the roof space is also a designated zone and is thermally assessed. Figures 5.26 and 5.27 show the installation of the roof trusses at the test houses. The 4-star timber floor house incorporates R3.5 ceiling fibreglass insulation over the entire ceiling area, while the 5-star timber floor and the concrete slab house have R4.0 fibreglass insulation over the ceiling area.

Figure 5.26: Installation of timber roof trusses onto the exterior stud wall

Figure 5.27: Interior view to the roof trusses and reflective sarking

Fourteen recessed halogen lamps were installed in the ceiling of the kitchen, dining and living area. The Australian Standards AS/NZS 3000 Wiring Rules specify a minimum gap of 200mm between the thermal insulation material and the recessed halogen light fittings. In order to upgrade the star-rating of the test houses, it was decided to supply a downlight guard over the light fittings. This method would allow the insulation to be installed flush to the downlight guard up to 50mm and then tapered off as shown in Figure 5.28 (Arrow Form 2007).

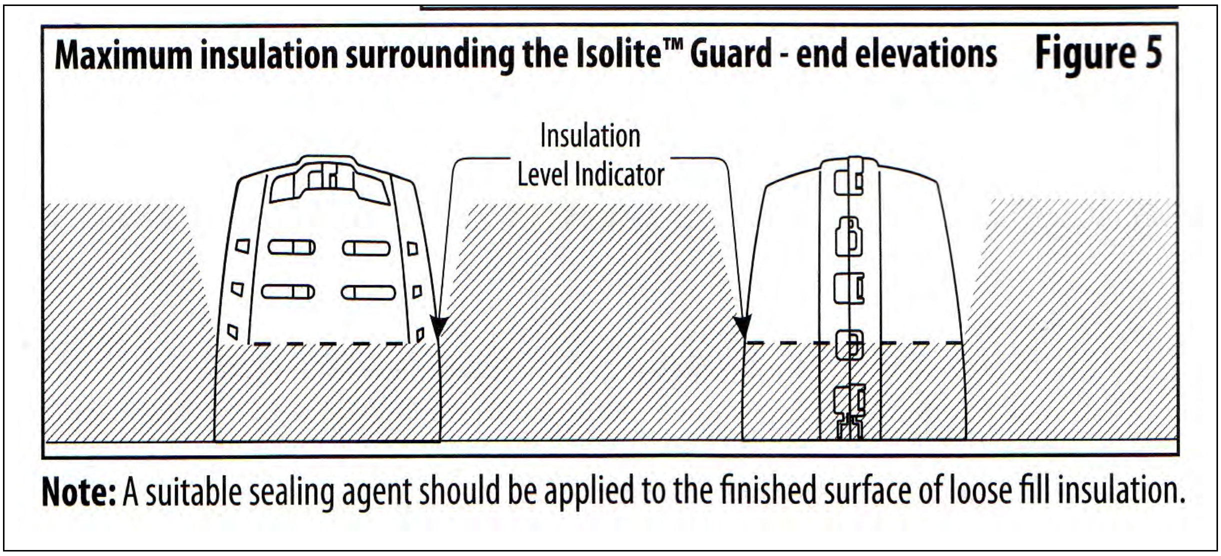


Figure 5.28: Installation instruction using the Isolite Guard around recessed light fittings (Source: Isolite Installation Instructions for Downlight Guard Model No 1721 & 1942)

When the electrician finally installed the downlight guards over the halogen light fittings he refused to install the insulation as recommended by the downlight guard manufacturer's installation instruction, and insisted on leaving a minimum gap of 200mm around each recessed light fitting and the insulation, as required by the AS 3000 Wiring Rules. The electrician adhered strictly to the regulation as required by the Australian Wiring Rules and seriously questioned the safety issues of the Isolite downlight guard installation instruction. The gaps left between the ceiling insulation and the downlight fittings were approximately 200- 300mm. Figure 5.29 shows the downlight fitting installed at the ceiling, Figure 5.30 shows the fibreglass ceiling insulation installed between the trusses and the ceiling joists and Figure 5.31 and Figure 5.32 depict the installation of the downlight guards over the recessed light fittings.

Figure 5.29: Internal view of a recessed ceiling downlight

Figure 5.30: Installation of ceiling insulation between ceiling joists

Figure 5.31: Installation of the downlight guards, leaving large gaps around the recessed light fittings

Figure 5.32: Installation of the downlight fittings

5.10. Summary

All three test houses were completed with the same quality and workmanship, in accordance with general building standards for residential housing. The houses were designed and constructed in accordance with current Australian building conventions.

There were only some minor construction variations to the original building plans, as follows:

- The roof insulation was not dished back to the recessed downlight guards and furthermore, a 200-300mm gap was left between the ceiling insulation and the downlight guards;
- Due to the slope of the building site, part of the concrete slab was constructed on fill (fine crushed rock) and not on the original existing ground line;
- Entry doors were installed without the specified weather seals;

- Carpet, complete with a rubber underlay, was installed over the concrete slab floor of the slab house. One of the original aims of this project was to compare the thermal performance of the timber floor with the concrete slab floor. However, due to the installation of the carpet over the concrete's thermal mass capacity, this comparison has been somewhat compromised. As the kitchen/dining/living area faces north-east to north-west, the large windows and sliding glass doors (window to floor area ratio 0.36) would have allowed ample solar radiation to be stored in the concrete slab floor.

Figures 5.33 to 5.36 show the completed test houses in Kingston.

Figure 5.33: The completed 5-star timber house

Figure 5.34: Inside view of the 5-star timber house

Figure 5.35: The slab house as seen from Auburn Road, Kingston

Figure 5.36: The housing development at Auburn Rd, Kingston, with the test houses at the right hand site of driveway

The installation of the monitoring equipment occurred simultaneously with the construction of the houses and most subcontractors were sympathetic and patient with the research team's installation of the cables, sensors and other equipment.

The following Chapter 6 describes the installation, testing and data acquisition of the monitoring equipment in the test houses.

Chapter 6: Thermal Monitoring Equipment, Installation and Data Acquisition

6.1. Introduction

Chapter 5 described the design and construction of the test houses and described minor construction changes made to the original building plans.

The first part of Chapter 6 discusses the selection and installation of monitoring equipment in the houses. The second part focuses on the data storage, acquisition and checking process in order to establish a reliable, high quality data set suitable for the empirical validation process. All monitoring equipment was installed during the construction of the houses, which began on 6 March 2007 with the preparation of the holes for the underground temperature sensors. The installation concluded on 29 June 2007, with the setting up of the weather station on the roof of the concrete slab floor house.

6.2. Instrumentation Requirements

The first task was to determine the instrumentation required to measure the environmental parameters of the houses and the on-site climate. This required the analysis of AccuRate's input and output data, with the aim of establishing similar data sets for the site-measured input data requirements. Inputs to AccuRate included data for the built fabric and the weather file. The relevant input data required are shown in Table 6.1.

Table 6.1: AccuRate's data input requirements

Subject	Measured Parameter	Units
Site Measurements	Dry bulb (air) Temperature (tenth of a degree)	ºC
	Moisture content (tenth of gram per kilogram	g/kg
	Atmospheric air pressure (tenths of kilopascals)	kPa
	Wind speed (tenth of metres per second)	m/s
	Wind direction	0-16, 0=calm. 1=NNW
	Cloud cover	0-8, 0=no cloud, 8=full cloud
	Global solar radiation	W/m²
	Diffuse solar radiation	W/m²
	Normal direct solar radiation	W/m²
	Solar altitude	0-90
	Solar azimuth	0º-359º. 0º=N, 90º=E
Thermal Performance Measurements of Test Houses	Temperatures of internal zones (tenth of degree)	ºC
	Temperatures of subfloor (tenth of degree)	ºC
	Temperatures of roof space (tenth of degree)	ºC

The air and globe temperatures were measured in the houses as discussed in Chapter 4.2.1. Other AccuRate inputs for thermal simulation include a default value for infiltration and internal heat loads for all internal zones of the house. Measurement of the air change rate per hour for the relevant zones in all three houses was required.

As well as monitoring air and globe temperature in the houses, the following parameters were also monitored as support data:

- Ground and sub-ground temperatures;
- North and South individual wall section surface temperatures;
- Roof section surface temperatures;
- Solar radiation at the houses' exterior walls;
- Moisture content in the subfloor roof spaces.

Monitoring equipment for the above-mentioned data was installed for the purpose of future research, such as the comparison of the test houses' thermal performance. Details of additional sensors are included in this chapter for documentation purposes only.

6.3. Sensor's Location Plan and Profile

The location of sensors in the houses was decided at the beginning of the project. As well as sensors aimed to collect data for the empirical validation, additional sensors were installed for future studies on the thermal performance of the houses. The locations of sensors during the three-week unoccupied stage (between 05 September, 2007 and 26 September, 2007) are shown in Figure 6.1.

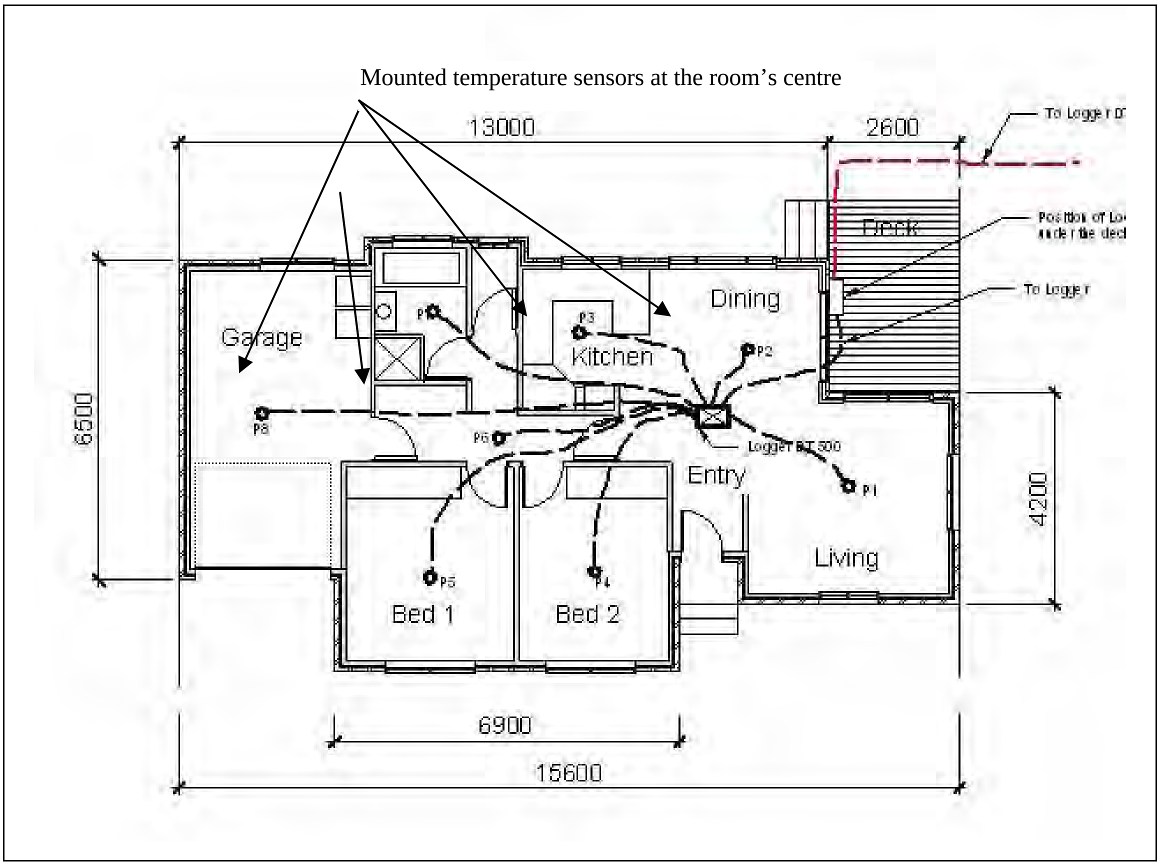


Figure 6.1: Location of poles with sensors attached at various heights levels

Dry bulb air temperature sensors at heights of 600mm, 1200mm and 1800mm from floor level were attached to timber poles placed in the centre of the rooms. In addition, a globe thermometer was attached to each pole at a height of 1200mm from the floor. Figure 6.2 shows the central timber pole with the attached temperature sensors and Figure 6.3 shows a globe thermometer attached to the timber pole.

Figure 6.2: Sensors attached to pole at 600mm, 1200mm and 180mm above floor level

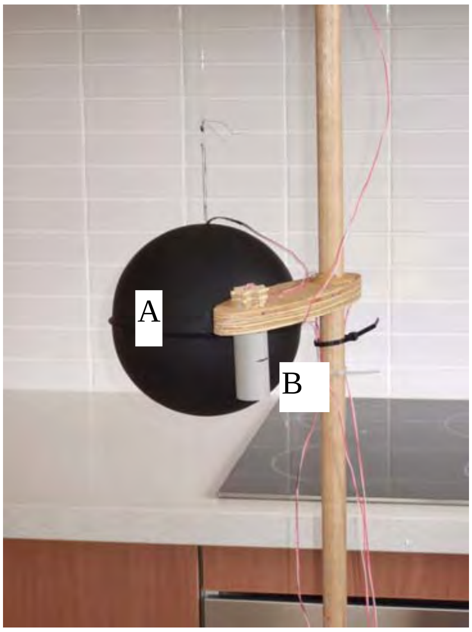


Figure 6.3: Globe thermometer (A) and dry bulb air temperature sensor attached to the inside of the plastic casing (B)

Additional temperature sensors placed inside the thermostat housing were attached to the walls of each room at a height of 1.2m above floor level. The exact location of the wall mounted sensors is shown in Figure 6.4 (below). These sensors, together with other monitoring equipment, were envisaged to provide backup temperature data collected at the centre of the rooms, and also to collect data for another three years for future performance comparison studies, which are beyond the scope of this project.

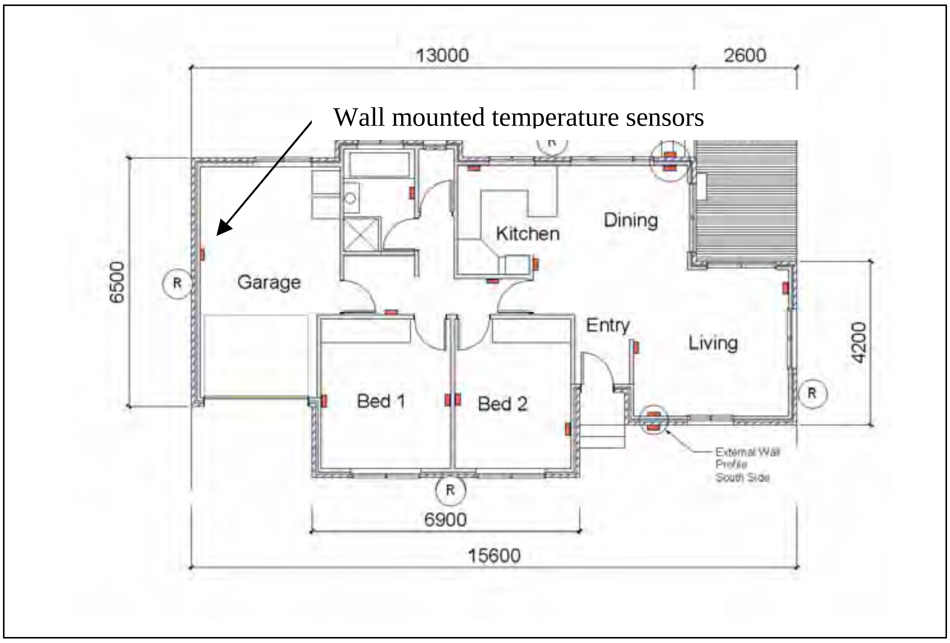


Figure 6.4: Location of permanent temperature sensors attached to the walls at a height of 1.2m from floor level

The location of sensors for the measurements of the vertical profiles for the 4 and 5-star timber floor houses and the concrete slab floor house are shown in Figure 6.5 and 6.6 (below).

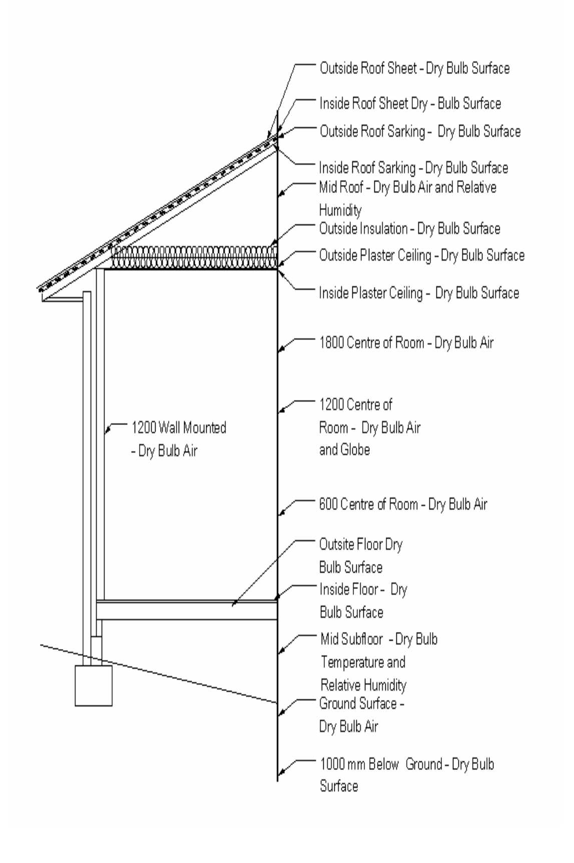


Figure 6.5: Vertical profile of measurements for the 4 and 5-star timber floor houses

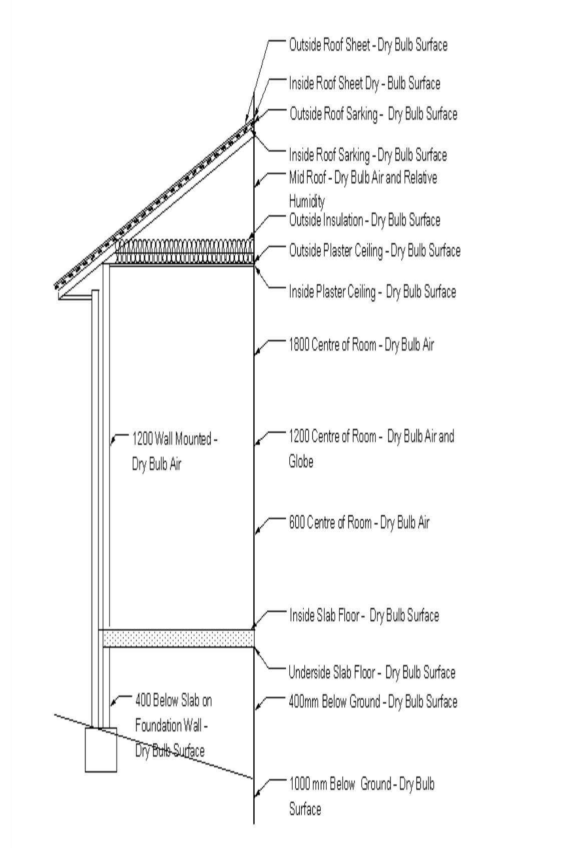


Figure 6.6: Vertical profile of environmental measurements for the slab house

One of the many measurements taken included the temperatures of the individual brick veneer wall components, that is, from the inside of the plasterboard wall to the exterior of the brick wall. Temperature sensors for the north-west and the south-east wall sections were installed for future studies on the heat flow through the wall section of the houses. In addition, vertical solar radiation was measured at all four sides of the houses, at a height of 1.2m from the internal floor level. Figure 6.7 shows the horizontal profile of measurements through the brick veneer wall section of the houses.

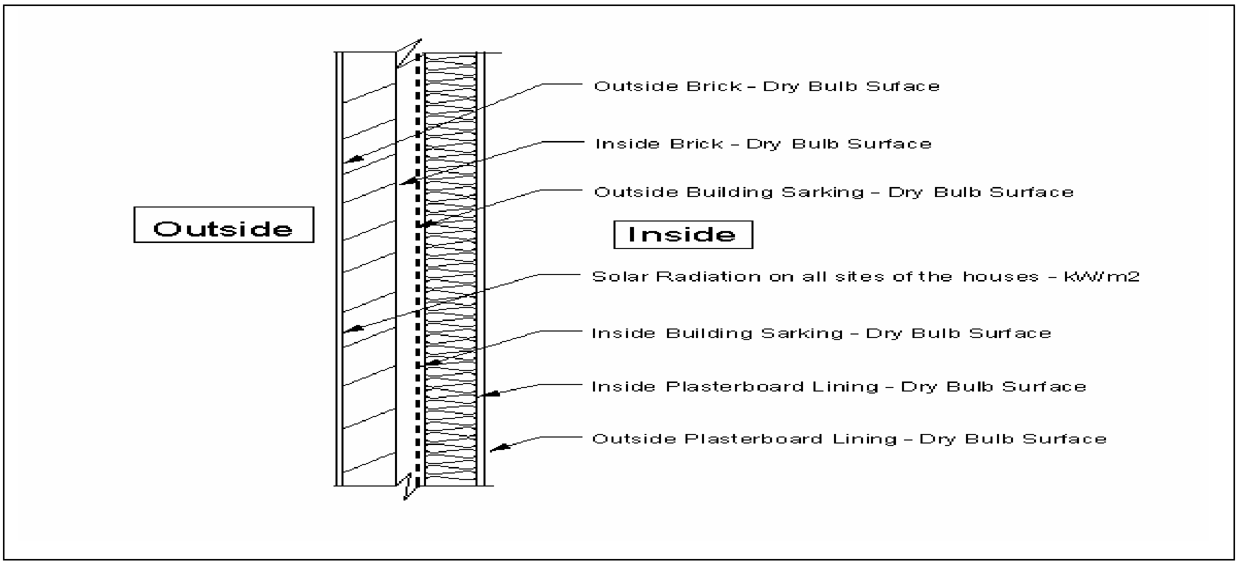


Figure 6.7: Horizontal profile of measurements through the north and south side of the brick veneer wall section of houses

6.4. The Monitoring Equipment

As mentioned in previous chapters, the selection of the data logger system and type of sensors for the test houses were the same as those used at the test cells in Launceston. At the start of the construction of the test houses in Kingston, monitoring equipment at the test cells in Launceston was already installed, tested and worked well. Useful experience and practical knowledge learned from the installation and operation of the monitoring equipment at the test cells in Launceston were than applied to the Kingston test houses. Using the same equipment also aids future comparisons between the Launceston test cells and the Kingston test houses.

6.4.1. The Data Logging System

a) Selection of the Data Logging System

There were two considerations in establishing the data management systems: firstly, the data acquisition and storage equipment should be remotely accessed from outside the test houses, and secondly, the system should be owned, operated and managed by the University of Tasmania's School of Architecture and Design.

The School of Engineering at the University of Newcastle, in conjunction with the Clay Brick and Paver Institute of Australia, constructed three test cells in Newcastle and successfully used an analogue data logger for their research management system (Sugo et al. 2004). The Australian Antarctic Research Division, which measured extreme climatic and thermal interior conditions, also successfully used analogue data loggers for their research. Several international projects described a preference for analogue data loggers and Dewsbury (2011) summarised some of their reasons for using the analogue system for the test cells as follows:

- Due to the low power consumed by an analogue data logger, which often included a battery power supply, the possibility of losing data during short power cuts was reduced;
- There was adequate software available to operate the data logger, minimising possible data logger failure due to software issues;
- Within the international research community this method of data acquisition had a long and proven history and as a result, there was a vast array of environmental measuring products available compatible with analogue date loggers;
- Amendments to the data logger programming can be done easily when sensors are added or removed for future research work to test buildings;
- Although the data logger had a limited on-board memory, this could be easily expanded with the addition of a static memory card;
- Data could be downloaded via a Local Area Network;
- A local specialist consultant was available to provide professional installation and service advice for this system. This was a very important factor for choosing this system.

With all the above factors considered, the selection of the analogue data logger system was deemed to be the appropriate choice for both the Launceston test cells and the Kingston test houses.

b) DT 500 Data Logger Programming and Installation

The Australian DT 500 series 3 data logger was used for the data acquisition and storage in this study. The original capacity of the internal memory was 13,650 individual readings, which was later expanded to a further 343,000 readings by adding a memory storage card into the data logger.

Figure 6.8 (below) shows the diagram connecting the sensors to the data logger.

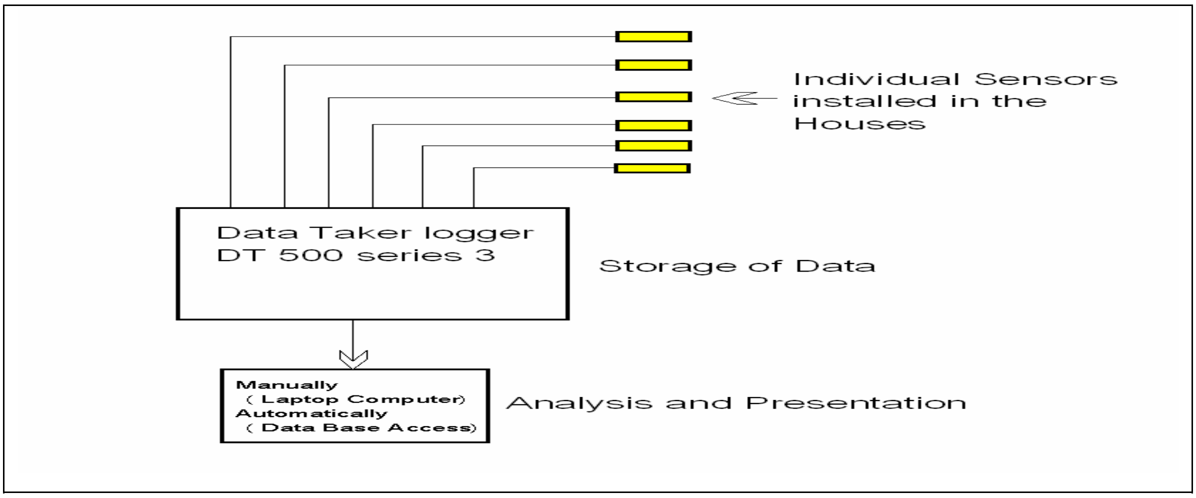


Figure 6.8: Connection of sensors to the data logger

Each data logger and channel expansion module arrived with a calibration certification. The appropriate wiring between the data logger, the internal channel expansion module and the RJ45 terminals to suit each sensor's measurement requirements was performed by a local Data Taker consultant. The data logger was installed into a metal case with an access door (Figure 6.9) and fixed to the exterior wall under the timber decking (Figure 6.10). Consequently, the metal boxes were not easily visible but still accessible for maintenance and manual data acquisition.

Figure 6.9: Data logger DT 500 and channel expansion module installed in the metal box

Figure 6.10: Installation of the data logger external metal box under the timber decking

All the data collected from the weather station were collected and stored in another data logger DT 80. This logger was Local Area Network (LAN) enabled and was interfaced directly with the

University’s building performance database in Launceston. The DT 80 logger’s data operation will be described under section 6.6.1, DT 80: data logger and local area network.

Each data logger required suitable programming to suit each sensor device recording the measured data. The data logger programs were divided into five separate sections.

The first part established the logger protocols; the second section defined the spans to the data logger operation; the third section defined the data and time; the fourth section determined the time step between measurements and the specific measuring device. For example, the command ‘RA10M D T’ programs the data logger to record a reading every ten minutes and the recorded data includes a time stamp. The channel allocation spreadsheet (as shown in Table 6.1 in this chapter) was an essential instrument of the channel loggers programming information. For example, the program column incudes the programming information in text form and an example is described in more detail as follows (Dewsbury 2011):

- 5+AD590(“P4NWC1200 AirT”,X,N) where
  5+ was the channel of the data logger of the attached sensor device
  AD 590 was the code that informs the logger of the type of sensor
  “P4NWC1200 AirT” was the text descriptor of the sensor device
  X, N was the command to inform the data logger on how to deal with the data.

The fifth section of the data logger programming instructed the data logger to commence operation. The program settings were prepared by the local Data Logger consultant Colin Hocking. Figure 6.11 (below) shows a sample of the data logger program setting.

```
' stage 1 - reset actions
H
CLEAR
\w1
RESET
\w4
' stage 2 - switches, parameters
/H
/e /R
/S
P14=600 P17=120 P26=30
99CV(W)=98989
P30=12
P36=0
S4=0,1,0,156"kW/m2" 'Irrad Sens No567
S5=0,1,0,159"kW/m2" 'Irrad Sens No556
S6=0,1,0,157"kW/m2" 'Irrad Sens No558
S7=0,1,0,156"kW/m2" 'Irrad Sens No559
S17=0,100,400,2000"%" 'Relative Humidity
S18=0,5,400,2000"m/s" 'Wind Speed hot wire anemometer
' stage 3 - Date, Time
D=\d


BEGIN
RA10M D T
1*AD590("Centre10 I/S DeckT",X,N) 1+AD590("Centre10 I/SCarpetT",X,N)
1-AD590("O/SSteelDeckAirT",X,N) 2*AD590("Centre10 I/SCeilingT",X,N)
2+AD590("O/SFFoilWrapAirT",X,N) 2-AD590("I/SSteelDeckAirT",X,N)
3*V(S17,"Centre10I/S-RH",X,N) 3+V(S17,"MidRoofSpaceRH",X,N)
3-V("Spare",X,N) 4*V("Spare",X,N) 4+V("Spare",X,N) 4-V("Spare",X,N)
5*V(S4,"O/SNorthWallIrr",X,N) 5+V(S6,"O/SEastWallIrr",X,N)
5-V(S5,"O/SSouthWallIrr",X,N) 6*V(S7,"O/S WestWallIrr",X,N)
6+AD590("SubGround2AirT",X,N) 6-V(S17,"UnderFloor2Humid",X,N)
1:1*AD590("NWall I/SPlyAirT",X,N) 1:1+AD590("NWall O/SPlyAirT",X,N)
1:1-V(S17,"NWall MidWallHumid",X,N) 1:2*V("NWall BaseWallHumid",X,N)
1:2+AD590("SWall I/S PlyAirT",X,N) 1:2-AD590("SWall O/SPlyAirT",X,N)
1:3*V(S17,"SWall MidWallHumid",X,N)  1:3+R("SWall BaseWallMoist",X,N)

END

/O
LOGON

G
```

Figure 6.11: Sample of DT 500 logger programming (Source: Hocking 2007)

6.4.2. Sensors

a) Selection of Dry Bulb Temperature Sensor

The test houses used the same type of sensors as those used in the Launceston test cells. A short description of the purpose of each sensor is provided below. Detailed information and specifications of all types of sensors are found in Appendix 2.

The dry bulb temperature in degrees Celsius (ºC) was required for measuring air and surface temperatures at various locations in the test houses. As AccuRate produces reports to a tenth of a degree Celsius, sensors with the same degree of accuracy were selected for this project. The temperature sensor chosen was a pre-calibrated Analogue Device type AD 592 CN. Nevertheless, these sensors were also calibrated on site. The AD 592 CN sensor is a two terminal monolithic integrated circuit temperature transducer, which provides an output current proportional to absolute temperature. Its operating temperature range is specified as -25ºC and

+105ºC with a measurement uncertainty of 0.3ºC minimum to 0.5ºC maximum at 25ºC. Figure 6.12 and Figure 6.13 (below) show the AD 592 CN temperature sensor installed at the wall of and at the centre of the rooms at three different height levels for the recording of dry bulb air temperature.

Figure 6.12: AD 592 CN temperature sensors attached to wall plate at the wall

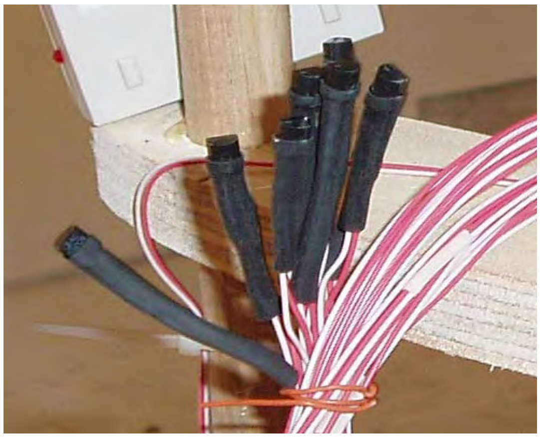


Figure 6.13: Numerous AD592 CN temperature sensors with bell wires attached for preliminary measuring of the air temperature at the centre of the room. This was only a temporary set up of seven sensors to compare the measurement of temperatures.

The dry bulb temperature sensor was the most frequent sensor used in this project with up to 63 sensors installed in each house.

b) Installation of Dry Bulb Air Temperature Sensors inside the House

Dry bulb temperatures were measured at various heights in the centre of internal rooms, roof space and subfloor space. To support and fasten off the sensors at the centre of the different rooms, an adjustable pole system was constructed which allowed for different rooms heights of the sensor devices. This pole system consisted of a 20mm diameter timber pole, a 25 mm plastic electrical conduit and square top and bottom plates. Figure 6.14 illustrates the detail of the temperature sensor affixed to the timber poles at the centre of the rooms. Three oval timber arms were fixed to each pole with hot glue at 600mm, 1200mm and 1800mm from floor level (Figure 6.15). Dry bulb temperature sensors were then installed inside the electrical conduits and attached to the oval timber arm. Where the sensor conduit faced direct solar radiation, the plastic conduit was covered by reflective foil paper (Figure 6.15 and 6.16).

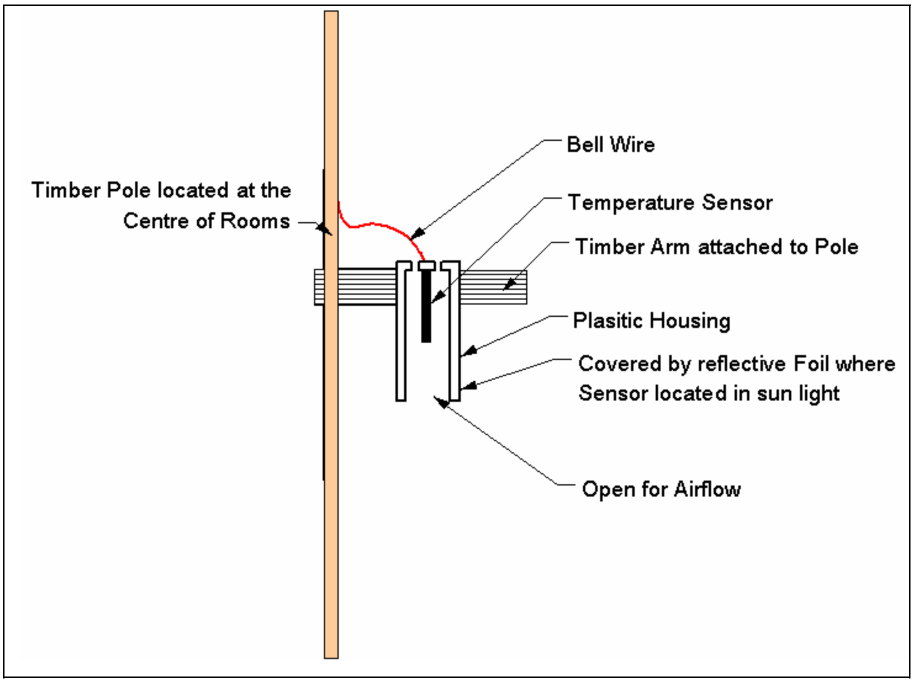


Figure 6.14: Air temperature sensor attachment to timber pole at the centre of rooms

Figure 6.15: Timber pole with temperature sensors located at different height levels

Figure 6.16: Temperature sensor fixed inside a plastic pipe, covered by reflective foil

In addition, additional air temperature sensors were mounted at two sides of the wall, one facing the inside room and one wall facing the exterior side of the room. The temperature sensors were placed inside the thermostat housing and attached to the walls at mid-wall height of the rooms. Figure 6.17 (below) shows the wall fixing details of the temperature sensors.

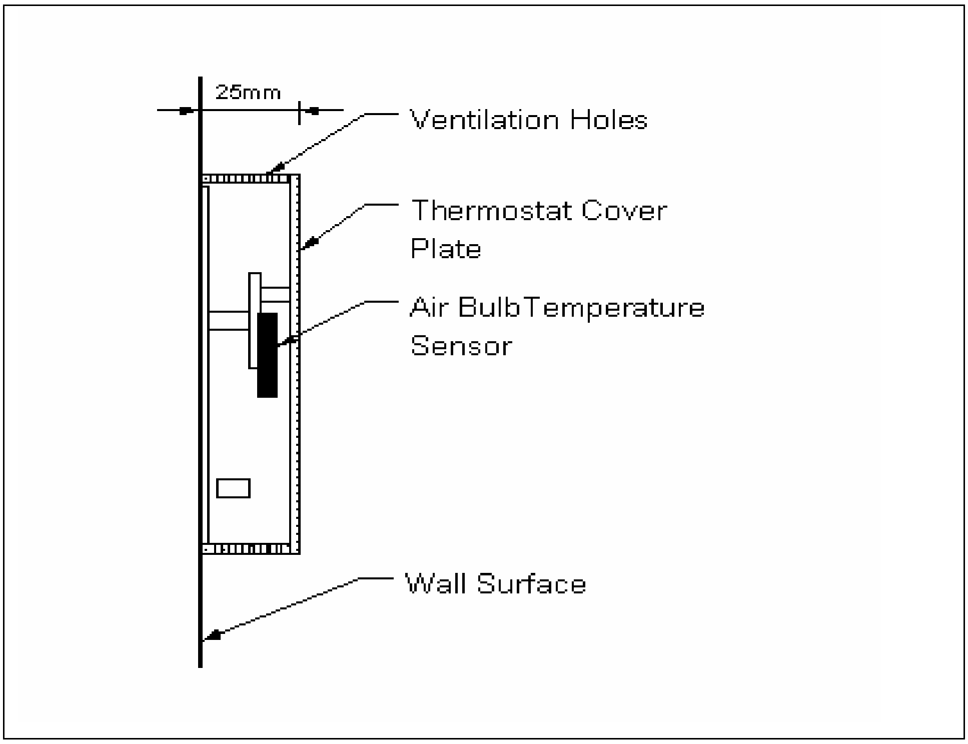


Figure 6.17: Wall-mounted dry bulb air temperature sensor and thermostat cover plate

The sensors attached to the timber poles at the centre of the rooms were removed after the free-running monitoring period, while the wall mounted temperature sensors remained in place to continuously record data for a further three years. Figure 6.18 shows the thermostat cover plate and Figure 6.19 the air temperature sensors fixed inside the thermostat housing onto the base plate.

Figure 6.18: Wall-mounted air temperature sensor located in a thermostat housing

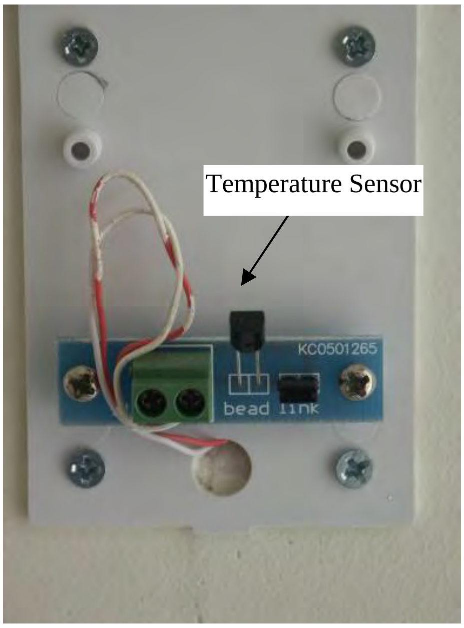


Figure 6.19: Wall-mounted temperature sensor with bell wire connection

c) Installation of Dry Bulb Air Temperature Sensors in the Roof Space and the Subfloor

Dry bulb temperature was also measured in the middle of the roof space and subfloor space. The temperature sensor was fixed to a timber pole using white cotton tape as shown on Figure 6.20. Figure 6.21 shows the timber pole located in the subfloor space of the 4 and 5-star timber floor houses with the temperature sensor and the humidity sensor attached to the pole.

Figure 6.20: Temperature sensor fixed to pole at mid-subfloor space hardly visible, refer to Figure 6.21 for detailed view

Figure 6.21: Temperature sensor fixed to pole at mid-subfloor space

d) Installation of Dry Bulb Surface Temperature Sensors

Surface temperatures of building materials were measured with the temperature sensors AD 592 CN. The temperature sensor's flat face was used to measure the surface temperatures and was fastened tightly to the surface being measured. The sensor was held in contact with the surface being measured, using an adhesive tape with similar emissivity or reflectance to the surface being measured. The adhesive tape also covered the sensor and insulated it to a certain degree from the layer of the surrounding air.

The vertical profile of the surface temperatures in the houses, as shown in Figure 6.5 and 6.6, included the following surfaces:

- Outside the metal roofing sheets;
- Inside the metal roofing sheets;
- Outside the roof sarking membrane;
- Inside the roof sarking membrane;
- Outside the insulation layer;

- Outside the plasterboard ceiling;
- Inside the plasterboard ceiling;
- Inside the floor under the carpet and carpet underlay;
- Underneath the floor;
- Ground surface (timber floor houses only);
- 400mm below the ground surface (concrete slab house only);
- 1000mm below the ground surface.

Figures 6.22 to 6.27 show some of the installation details of the temperature sensors to the different building materials.

Figure 6.22: Temperature sensors attached to the outside of roof

Figure 6.23: Temperature sensors taped onto inside of roof sarking with reflective silver adhesive tape

Figure 6.24: Temperature sensor attached to the inside of ceiling before being plastered over

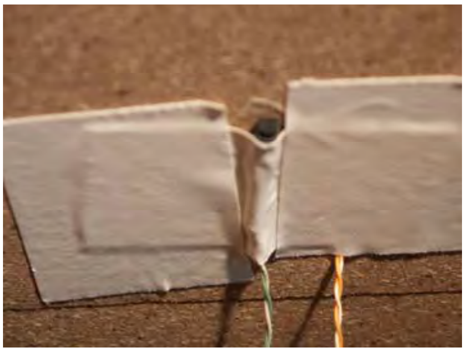


Figure 6.25: Temperature sensor attached to the underside of the timber floor (glued and taped)

Figure 6.26: Installing the sensor to the interior side of the slab floor

Figure 6.27: Installing the waterproof temperature sensor housing and wire connection for the temperature sensor 1m below ground surface of the slab house

Generally the temperature sensors were glued (only the body of the sensor, not the flat sensor part) and taped to the various building materials. The temperature sensor attached to the inside of the slab floor was inserted and glued into a small groove in the concrete slab and the surface was then covered with mortar. The temperature sensors located 1m below the ground surface were inserted in a water-proof plastic housing, with two bell wires inserted in small diameter waterproof plastic conduits, as depicted in Figure 6.27. The surface temperature of the individual members of the north and south wall were also measured and this included:

- Outside the brick wall (under the external layer of render);
- Inside the brick surface;
- Outside the building sarking;
- Inside the building sarking;
- Outside the plasterboard lining; and;
- Inside the plasterboard lining.

Figures 6.28 to 6.33 show details of some of the above-mentioned installation of sensors, which were glued and taped to the individual building materials. Figure 6.28 shows the sensor was inserted into the groove of the plaster board wall which was then plastered over. The sensors, as shown in Figure 6.29 and 6.30, were attached to the sarking with a silver-faced tape. The sensors were glued and taped to the inside of the brick wall, as shown in Figure 6.31and 6.32. The sensors were inserted in a small hole in the outside of the brick wall, as shown in Figure 6.33. Finally the brick wall was rendered over, making the sensors invisible from the exterior wall.

Figure 6.28: Sensor attached to the inside of the plasterboard wall

Figure 6.29: Sensor attached to the inside of the sarking

Figure 6.30: Sensor attached to the outside of the sarking

Figure 6.31: Sensor before being attached to the inside the of brick wall

Figure 6.32: Sensor attached to the inside of the brick wall with red cloth tape

Figure 6.33: Sensor attached to the inside of the brick wall with red cloth tape

All dry bulb surface sensors were installed for the purpose of thermal performance analysis between the different house construction types and for further studies on the thermal performance of individual wall systems. For validation purposes, the surface temperatures were not used to provide input data for the AccuRate software.

e) Installation of Globe Thermometers

The globe temperature depends on both convective and radiative heat transfer (Environmental Design: CIBSE guide A). Because of convective air movements the globe temperature lies between the air temperature and the mean radiant temperature. The faster the convective air moves over the globe thermometer the closer the globe temperature approaches the air temperature. If there is zero air movement, globe temperature and mean radiant temperature are equal. As the test houses were monitored in closed conditions it can be suggested the internal convective air movements were minimal and that the globe temperature were closer to the mean radiant temperatures. The globe thermometers were installed in reference to Delsante (2006) that globe temperature is likely to be closer to AccuRate's predicted output temperature.

The globe thermometers were made at the University's School of Architecture and Design according to the ASHRAE 2006 specification. They consisted of a 150mm diameter hollow ball made of copper, coated with a matt black paint and one AD 592 CN temperature sensors was fixed at the centre of each sphere. Figure 6.34 shows the air temperature sensor being attached to the centre of the copper ball, while Figure 6.35 shows the completed globe thermometer attached to the timber pole at a height of 1.2m from the floor level of the rooms.

Figure 6.34: Inserting the air temperature sensor into the globe thermometer

Figure 6.35: Globe thermometer measuring environmental temperatures

f) Installation of the Humidity Transmitter

The Vaisala HMW40 humidity transmitter was chosen because it was especially designed for energy management systems in buildings. The operation range is between 0 and 100%RH with a measurement of uncertainty of ±3% @ +20ºC. Figure 6.36 shows the installation of the humidity transmitter at the subfloor of the test houses. The humidity transmitters were located at mid-height of the ceiling space of all three houses and at the subfloor space of the two timber floor houses. The transmitters were attached to a timber pole with glue and a white cloth tape as shown in Figure 6.37. The collection of the humidity data in the subfloor and roof space of the houses was not part of the validation process, but was collected for further thermal performance research analysis.

Figure 6.36: Humidity transmitter installed in the ceiling space

Figure 6.37: Humidity transmitter located in the subfloor space

g) Installation of the Solar Pyranometer

Solar radiation data were measured at each of the four walls of the three houses and also on the roof of the slab floor house, as part of the weather station measuring global horizontal and global vertical north facing solar irradiance. Based on its technical specification to measure solar irradiation in W/m² and its cost, the SolData 80SPC pyranometer was chosen for this project. The pyranometer consisted of a calibrated solar cell that generates electricity when solar radiation impacts the surface of the solar cell. All SolData SPC pyranometers are calibrated by the Fraunhofer-Institute for Solare Energiesyteme against a first class Kipp-Zonen CM21 reference pyranometer with a total uncertainty of 3%. Each pyranometer was delivered with a user guide providing a calibration factor K expressed as mV/(kW/m²). For example, if the K is 160mV/(kW/m²) when the solar radiation S is 1 kW/m², the pyranometer will provided an output voltage of 160mV. Each pyranometer was then re-calibrated, with each individual K-calibration factor using the required equation (S=U/K) to achieve actual irradiation values (W/m²). Figure 6.38 shows the pyranometer attached to each of the four walls of the houses and Figure 6.39 shows the horizontal and vertical fixed position of the pyranometer on the roof of the slab house.

Figure 6.38: SolData 80SPC pyranometer fixed to four external walls of test houses measuring solar radiation on the walls

Figure 6.39: SolData 80SPC pyranometer installed on the roof as part of the weather station measuring global and north vertical solar radiation

h) Installation of the Weather Station

In addition to global solar radiation, the site weather station installed on the roof of the slab floor house also measured: air temperature, relative humidity, wind speed and wind direction.

With the view that temperature and humidity data were required to a tenth of a degree Celsius and relative humidity to match the AccuRate data, the Vaisala HUMICAP HMP 45A/D humidity and temperature sensor was selected. The probes have a temperature range of -39.2ºC to +60ºC with an uncertainty of ±0.2ºC at 20ºC, and a humidity measuring range of 0.8 to 100% RH with an accuracy of ±2% at 20ºC between 0 and 90% RH.

For the measurement of wind speed and wind direction a large range of sensors were available, including the impeller type, which generally would have provided a more accurate reading. However, the cost of the impeller type could not be justified and the less expensive Pacific Data System PDS-WD/WS-10 with a 3-cup anemometer and separate wind vane was selected for this project. This system also satisfied the requirement of the wind speed to be measured to a tenth of a metre per second. The wind speed sensor has a DC generator element type with a sensor output of 0 to 1000mV for an actual wind speed of 0 to 100 km/h. The wind direction sensor has a 360 degree rotary potentiometer element type with an electrical dead-band of 5 degrees. The sensor output ranges from 0 to 1000mV for a 0 to 360 degree of wind direction. Figure 6.40 shows the weather station located on the roof of the slab floor house, including the 3-cup anemometer, wind direction van and the combined temperature and humidity sensor probe.

Figure 6.40: Site Weather Station installed on top of the roof of the slab floor house

While all other measuring sensors were connected to the data logger DT 500, the weather station was directly connected to the DT 80. Figure 6.41 shows the DT 80 and the temperature read-out screen during manual data acquisition.

Figure 6.41: DT 80 indicating air temperature at the weather station

6.4.3. Cabling and Wiring of Sensors to Data Logger

The wiring and cabling method used for to the Launceston test cells was adapted for the Kingston test houses. Wiring was provided to the following items:

- The Data Taker DT 500 logger and channel expansion modules for the data acquisition and storage;
- From the data logger's internal terminals to the external RJ45 terminal blocks;
- Eight wire data cable (Cat 5 cable) from the RJ 45 data logger terminal blocks to the Krone connector, which was fixed close to the particular sensors;
- Two-wire sensor feeder cables (bell wires) from the Krone connector to the individual sensors. The sensor feeder cable was soldered to the sensor's connection wires.

Figure 6.42 illustrates the wiring concept of the measuring equipment, starting from the data logger with the eight wire data cable connecting to the Krone connector plate with a RJ 45 plug and continuing from the Krone's bell wire connection leading to the individual sensors installed around the house.

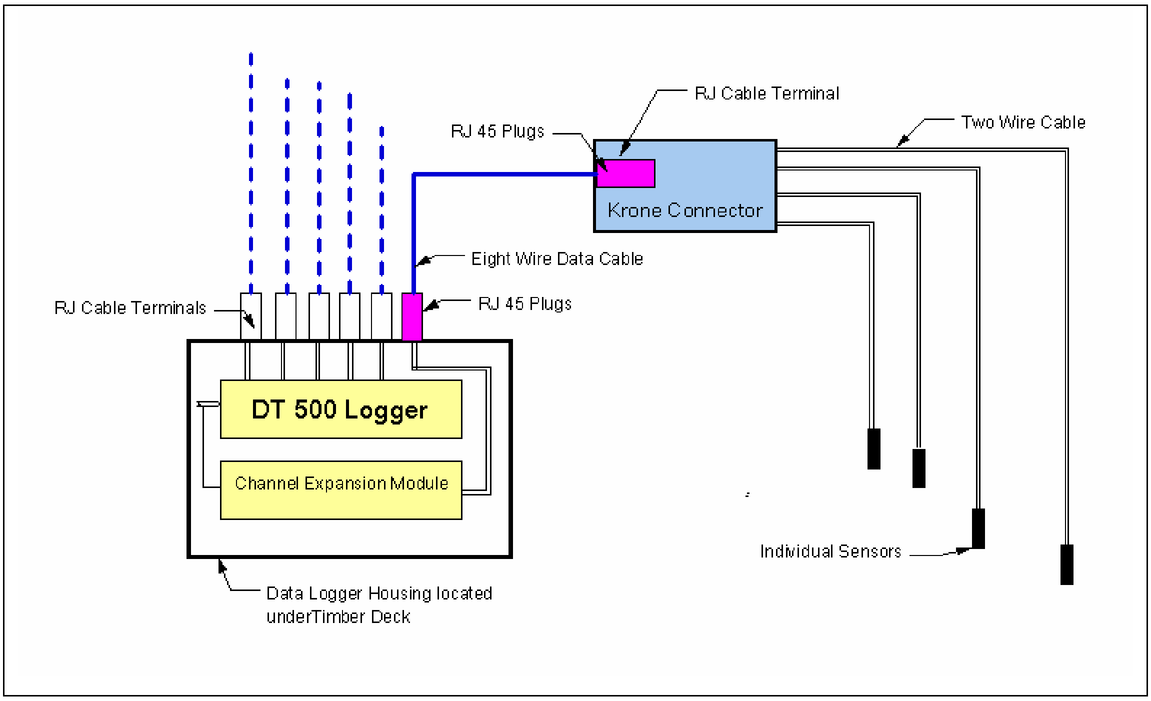


Figure 6.42: Wiring diagram for the cabling and wiring connection between the data logger and the individual sensors installed in the houses

The use of an eight-wire data cable allowed each data cable to carry the signal of four individual measuring devices. Extensive planning and careful layout of sensors allowed a maximum configuration of all data logger channels. Table 6.1 shows a sample of one of the data logger's DT 500 channel allocation spreadsheets for the 4 and 5-star timber floored house.

Table 6.2: Sample of the DT 500 channel allocation spreadsheet for the 4 and 5-star timber floor house

4 and 5 star timber foor house

Chan No	Chan Type	DT Channel	DT Input Connr	Colour	SensorCode Prefix	Program	Location	Descr 1	Descr 2	Descr 3	Function	Sensor Ref
1	Current V1	1*	1A1	Blue/Wh	1B	1*V	Electrical 1	Main Power In	Mains Power In	Current Transformer		
2	Current V2	1+	1A2	Green/Wh	1B	1+V	Electrical 1	Stove/Oven	Stove/Oven	Current Transformer		
3	Current V3	1-	1A3	Orange/Wh	1B	1-V	Electrical 1	HWS	Humidity	Current Transformer		
4	Current V4	2*	1A4	Brown/Wh	1B	2*V	Electrical 1	Kitchen GPO	Kitchen GPO	Current Transformer		
5	Current V5	2+	1B1	Blue/Wh	1B	2+V	Electrical 2	Hard Wired heater	Hard wired heater	Current Transformer		
6	Current V6	2-	1B2	Green/Wh	1B	2-V	Electrical 2	Other GPO	Other GPO	Current Transformer		
7	Voltage	3*	1B3	Orange/Wh	1B	3*V("Spare",X,N)	Electrical 2	Spare	Spare	Spare	Spare	
8	AD592CN	3+	1B4	Brown/Wh	1B	3+AD590("Garage Ext Wall AirT",X,N)	Garage 1	Garage ext wall	Air Temp	Ext Wall	Air Temp	
9	AD592CN	3-	1C1	Blue	1B	3-AD590("Bathroom Int Wall AirT",X,N	Walls 1	Bath Int Wall	Air Temp	Internal V	Air Temp	
10	AD592CN	4*	1C2	Green	1B	4*AD590("Kitchen Int Wall AirT",X,N)	Walls 1	Kitch Int Wall	Air Temp	Internal V	Air Temp	
11	AD592CN	4+	1C3	Orange/Wh	1B	4+AD590("Kitchen Ext Wall AirT",X,N)	Walls 1	Kitch ext wall	Air Temp	Ext Wall	Air Temp	
12	AD592CN	4-	1C4	Brown/Wh	1B	4-AD590("Dining Ext Wall AirT",X,N)	Walls 1	Dine ext Wall	Air Temp	Ext Wall	Air Temp	
13	AD592CN	5*	1D1	Blue/Wh	1B	5*AD590("Living Ext Wall AirT",X,N)	Walls 2	Live Ext wall	Air Temp	Ext Wall	Air Temp	
14	AD592CN	5+	1D2	Green/Wh	1B	5+AD590("Living Ext Wall AirT",X,N)	Walls 2	Live Ext wall	Air Temp	Ext Wall	Air Temp	
15	AD592CN	5-	1D3	Orange/Wh	1B	5-AD590("Bed 2 Ext Wall AirT",X,N)	Walls 2	Bed 2 Ext Wall	Air Temp	Ext Wall	Air Temp	
16	AD592CN	6*	1D4	Brown/Wh	1B	6*AD590("Bed 2 Int Wall AirT",X,N)	Walls 2	Bed 2 Int wall	Air Temp	Internal V	Air Temp	
17	AD592CN	6+	2A1	Blue/Wh	1B	6+AD590("Bed 1 Ext Wall AirT",X,N)	Walls 3	Bed 1 Ext Wall	Air Temp	Ext Wall	Air Temp	
18	AD592CN	6-	2A2	Green/Wh	1B	6-AD590("Bed 1 Int Wall AirT",X,N)	Walls 3	Bed 1 Int Wall	Air Temp	Internal V	Air Temp	
19	AD592CN	7*	2A3	Orange	1B	7*AD590("Hall Int Wall AirT",X,N)	Walls 3	Hall 1 Int Wall	Air Temp	Internal V	Air Temp	

The channel allocation spreadsheet provided a detailed cabling and wiring connection diagram of the monitoring system.

The following Figures 6.43 to 6.48 show several key wiring and connection details. Figure 6.43 illustrates temperature sensors connected to the bell wire before installation into the various sections of the brick veneer wall. Figure 6.44 depicts the data cables installed within the hallway’s wall cavity, connecting the data logger to the sensors, via the Krone connectors in the roof space. Figure 6.45 shows the installation of the Krone connectors, providing the link between the data cables, from the data logger to the bell wire, feeding all the individual sensors. Figure 6.46 shows the Krone connectors in the subfloor fixed to the underside of the floor joist with the data cable and bell wire connections. Figure 6.47 shows all the data cables connected to the data logger with RJ 45 plugs. Finally, Figure 6.48 shows the data logger and the interior wiring connection of the data cables to the RJ 45 cable terminals in the metal box.

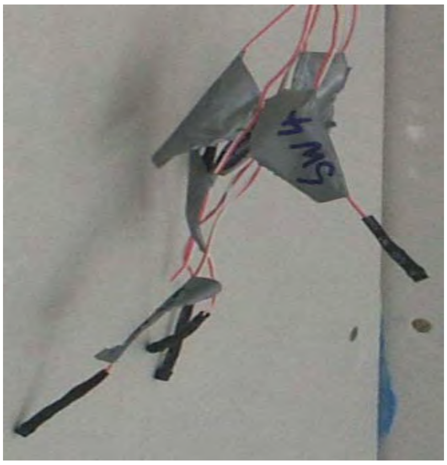


Figure 6.43: Temperature sensors attached to bell wire

Figure 6.44: Installation of data cables connecting sensors to Data Logger

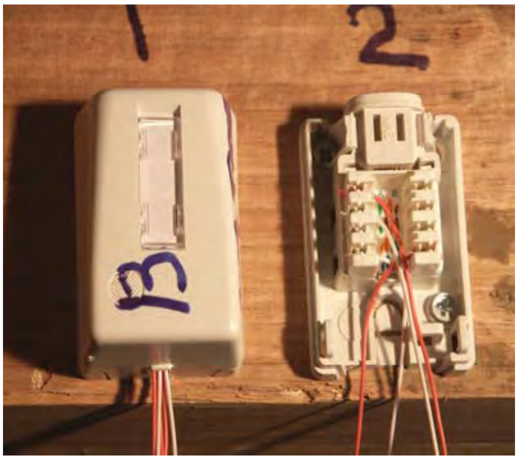


Figure 6.45: Krone connectors connecting data cables to sensors via bell wires

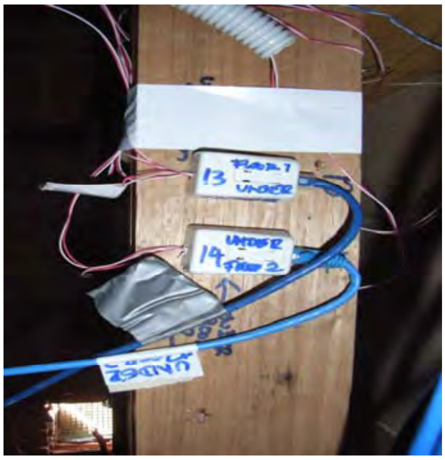


Figure 6.46: Krone connectors fixed to the floor joist connecting data cable to bell wire

Figure 6.47: Data cable connecting to data logger with RJ 45 plugs

Figure 6.48: Data cable and RJ 45 plugs connection to the data logger’s RJ 45 terminal

The installation of the wires within the houses took considerable time, and special care was taken that all the cables connected to the Krone connectors and individual wiring to the sensors were kept at least 600mm away from any other electrical house wiring.

a) Testing of Cable and Wiring Connections

There were two distinctive data logger wiring stages: the internal data logger wiring and the wiring from the data logger to all the individual sensors. The wiring within the data logger was installed by the Data Logger consultant involving the following process:

- Step 1: All data from the logger was emptied followed by data logger tests runs and checks to ensure that all channels read zero;
- Step 2: The data logging program was installed into the data logger and all channels were checked to ensure that a zero reading was still recorded;
- Step 3: Resistors and other wiring were installed to the individual channels of the data logger. The data logger was tested to ensure that a zero value was still recorded;
- Step 4: Earth reference wires were installed. The data logger was tested to ensure a zero value was still recorded;
- Step 5: The data cables were attached to the R45 terminal blocks and the data logger was tested to ensure a zero reading was still recorded.

This method for wiring the data logger, (from the data logger individual channels to the RJ terminal block) enabled removal or repair of any items which did not present a clean signal. During the beginning of the three months data collection, occasional testing of the data loggers was performed when all data cables were removed from the logger terminal and all wires were tested to ensure a zero reading was still recorded.

A simple step-by-step data cable testing, (RJ plug connection to the data logger and sensor feeder cable to the sensors) was introduced for the houses, based on the wiring methods at the test cells at Launceston. The procedure for the installation of cables, wires and cable connectors is described in more details as follows:

- Step 1: The data cable was cut to the desired length between the Logger (placed on the external wall under the deck) and the Krone connector block. The first RJ 45 plug was connected to the data cable and the cable was plugged into the terminal block of the data logger. The eight individual cables outlets were then tested at the other side to ensure a zero reading (-273.4ºC) when connected to the computer (Figure 6.49);

- Step 2: The second RJ 45 was attached to the data cable and the data logger was tested to ensure a zero value (-273.4ºC) reading (Figure 6.50);
- Step 3: The RJ 45 plug was now connected into the Krone connector block and the data logger was tested to ensure a zero value recording (Figure 6.50);
- Step 4: The sensor feeding cable (bell wires) was wired into the Krone connection block with the sensors already wired to the feeder cables. A temperature signal was then received. (Figure 6.51);
- Step 5: Output readings were then compared between data: from the data cabled sensor via the sensor feeder cable and the Krone connector block and data from direct-wired sensors at the same location. If there was a variation of more than 0.3ºC of the readings, individual sensors were replaced until similar readings were recorded. Only one cable sensor was replaced during the sensor test comparisons and the remaining comparison between the cabled sensor and the direct wired sensors showed similar readings of not more than 0.2 ºC difference (Figure 6 52).

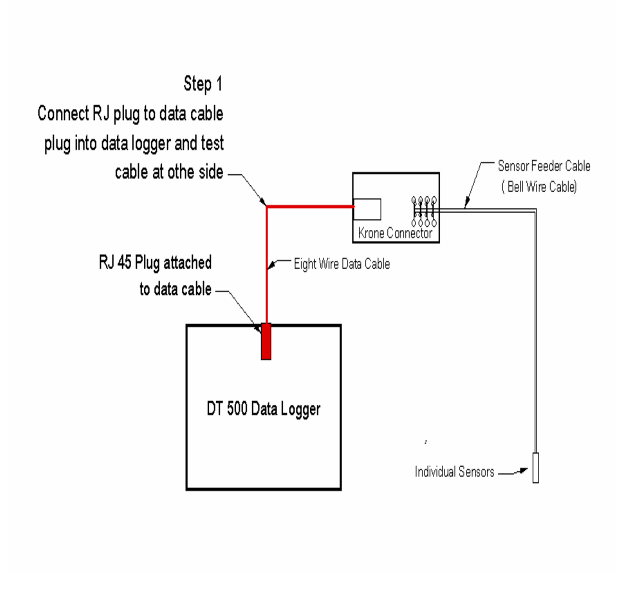


Figure 6.49: Step 1. Installation and testing of data cable and plug connection

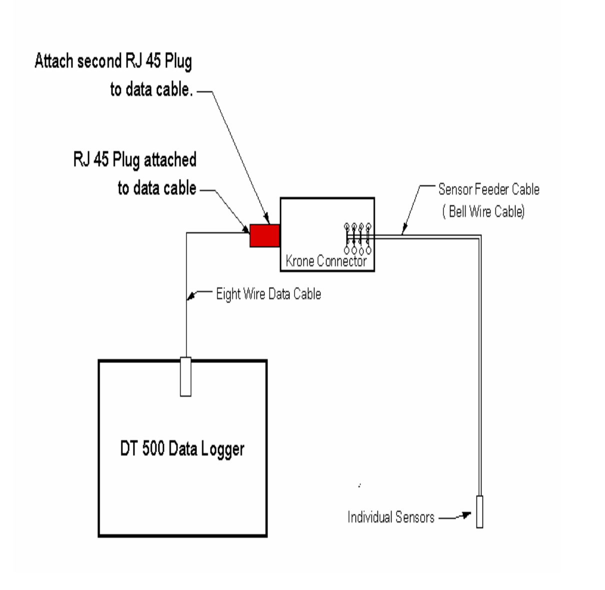


Figure 6.50: Step 2. Attaching second RJ 45 plug to data cable

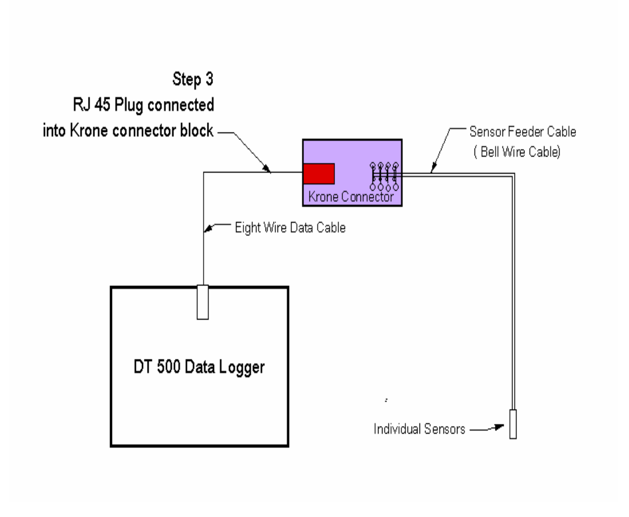


Figure 6.51: Step 3. Connecting the RJ 45 plug into the Krone connector

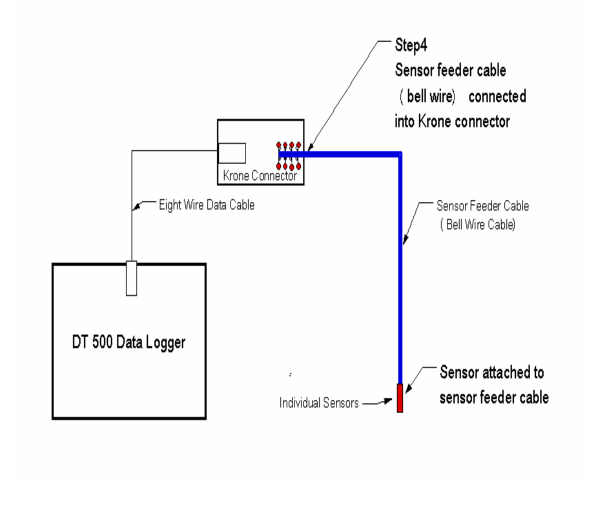


Figure 6.52: Step 4. Connecting the sensor feeder cable into the Krone connector block

The testing of the individual cable and plug connections permitted a reliable error examination. Most of the error readings were due to poorly connected RJ plugs to the data cables and faulty attached wires into the Krone connectors. In this case the data cable would be trimmed and a new RJ 45 plug would be attached to the cable. For a faulty wire connection into the Krone connector, the wires were removed trimmed and re-connected.

The installation and testing of each individual cabling and plug connection was time-consuming, with many inquisitive builders and sub-contractors at the building site wondering about our intensive measuring activities. Figure 6.53 shows the installation of the sensor feeding cable and the subsequent testing of the cable and Figure 6.54 depicts the computer zero readout (-273.4ºC) for the testing of the cable and plug connections.

Figure 6.53: Connecting and checking sensor feeder cable on site

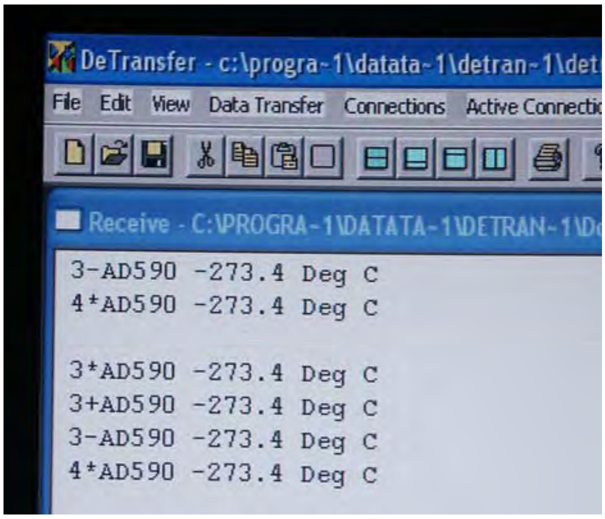


Figure 6.54: Checking cable connection and data logger's zero value readouts

6.5. The Infiltration Test

AccuRate required data input for the heat losses due to infiltration. Infiltration was measured at the following zones:

- The roof space;
- The kitchen/dining/living area;
- The subfloor of the timber floor houses.

The measurement of infiltration in the three houses was conducted by the Mobile Architecture & Built Environments Laboratory (MABEL) from Deakin University, Geelong. Building air leakage and the air change rates were determined using the simultaneous fan pressurization method (FPM) test and the tracer gas decay method (TGDM). The tests comprised three different approaches, (Luther 2008) namely:

- A fan pressurisation test solely on its own, undergoing the various pressures from 4 Pa to 50 Pa;
- A tracer gas decay method that investigated a continuous cycle of dosing and decay;
- A simultaneous test conducted in 4, 8 and 20 Pa stages. For each stage of the FPM the blower door was fixed to a continuous pressure level. A tracer gas was introduced at a high concentration level within the measured space, allowing the decay to be observed under the specific set pressure through the tracer gas decay method.

Figure 6.55 shows the comfort cart measurement equipment set up for the tracer gas decay test, Figure 6.56 the tracer gas graph on the computer screen, Figure 6.57 the installation of the blower door test unit and Figure 6.58 the blower door pressurisation fan. The infiltration was conducted to achieve realistic measured air change rates in the roof space, interior rooms and the subfloor of the timber floor houses. The measured air change rate data was then used as part of the AccuRate simulation for the empirical validation.

Figure 6.55: Comfort cart measurement equipment

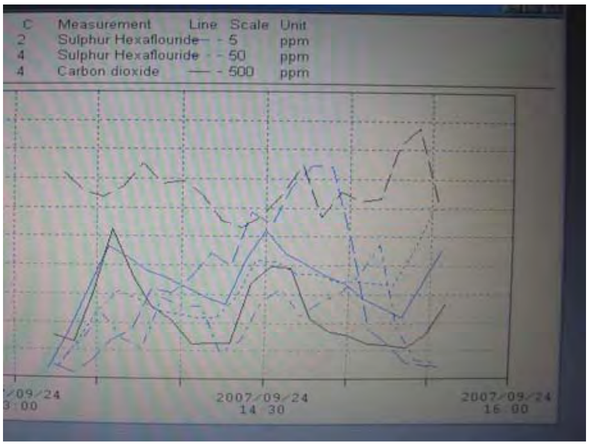


Figure 6.56: Tracer gas computer graph

Figure 6.57: Interior view of the blower door equipment installed at the test houses

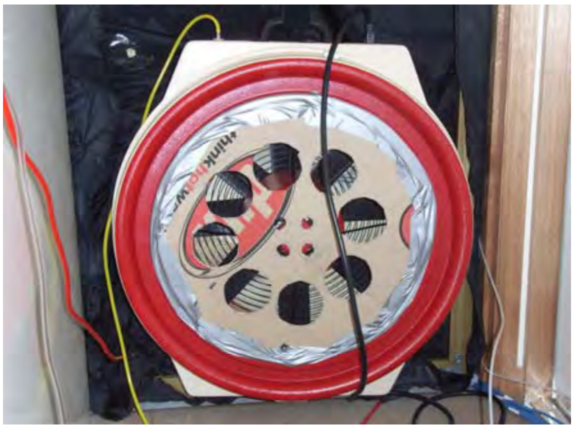


Figure 6.58: View of the pressurisation fan of the blower door equipment

6.6. Data Management and Processing

The data management and processing, developed for the research at the test cells in Launceston (Dewsbury 2011), was also adopted for the test houses in Hobart. Data procedures covered the following activities:

- The storage of data in the data logger;
- Downloading of data from the data logger;
- Storage of data to a laptop computer and database;
- Data checking and cleaning, and averaging of data values.

The initial data logger acquisition was the manual downloading of data from the data logger to the laptop computer which occurred between 5 July 2007 and 1 January 2008. At the start of the data acquisition the DT 500 data logger could store between two and three weeks of data, requiring access to the loggers at least every two weeks. The data was saved on the computer in two different formats, namely: in the original format of the data logger's downloading 'De Transfer' program and subsequently, as a comma separated value (CSV) format. The data was then stored at the School of Architecture and Design's database. Figures 6.59 and 6.60 show the manual downloading process from the data logger to the computer.

Figure 6.59: Manual downloading of data from the data logger to the computer

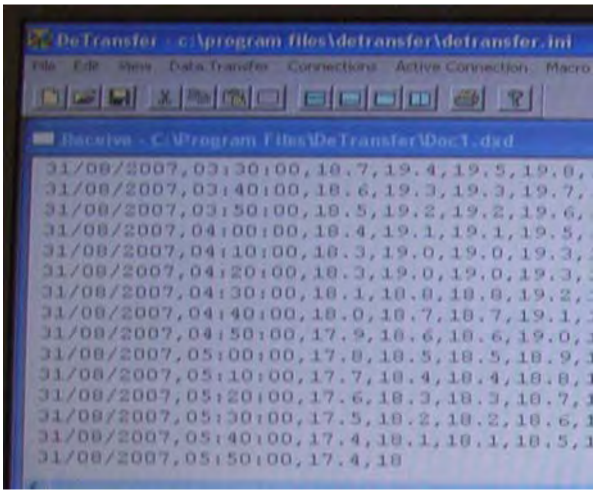


Figure 6.60: Downloading data with the De Transfer program to the computer

A series of power interruptions during the first three months of data acquisition resulted in loss of some data. In order to avoid this problem, an 1MB static memory card was added to the logger. The additional memory card increased the storage capacity of the logger to about six weeks, with data now being stored directly to the memory card. Despite a power failure, the data was now retained in the memory card. The increased storage capacity of the loggers initially reduced the frequency of manual downloading, but it was soon realised this also reduced the checking mechanism for sensors functioning incorrectly; therefore, subsequently, the frequency of downloading data returned to a fortnightly interval. It was then realised, that the data acquisition and storage system had to be improved, especially in regard to the recognition and prompt reporting of invalid or faulty data. The system was improved with the additional data logger DT 80 installed on site. It was now possible to collect the data from a single logger, requiring access to one house only. Figure 6.61 shows the installation of the DT 80 logger at the slab floor house.

Figure 6.61: DT 80 data logger installation

Table 6.2 shows a summary of methods of data acquisition and storage for the test houses.

Table 6.3: Methods of storing data for the Test Houses

Data Storage Method	**Period of Collection**	**Data Storage Capacity**	**Collection Method**
Data Logger with internal memory	Every ten minutes	2-3 weeks	Manually
Data Logger with memory card	Every ten minutes	5-6 weeks	Manually
DT 80 Logger	Copied from DT 500 every ten minutes	6-8 weeks	Manually
DT 80 Logger with LAN interface	Copied from DT 500 every ten minutes Transmitted to the research centre server every ten minutes	Unlimited (depending to storage capacity of server) Back up to 6 weeks data stored on memory card	Automated

The server was now programmed so that the downloaded data were placed in the principal file and also in a second backup file for access by the research staff.

6.6.1. DT 80 Data Logger and Local Area Network (LAN)

Initially the data was downloaded manually on site from the DT 500 and DT 80 to a laptop computer. Eventually downloading was automated through the LAN-enabled DT 80. It was programmed to collect the data from the DT 500 logger and to send and receive data from the computer and server located at the University's research office. In addition, the DT 80 data logger provided the data acquisition function for the weather station located at the site.

The cabling method required for the DT 80 connection to the DT 500 data logger, weather station and external server is shown in Figure 6.62 (below).

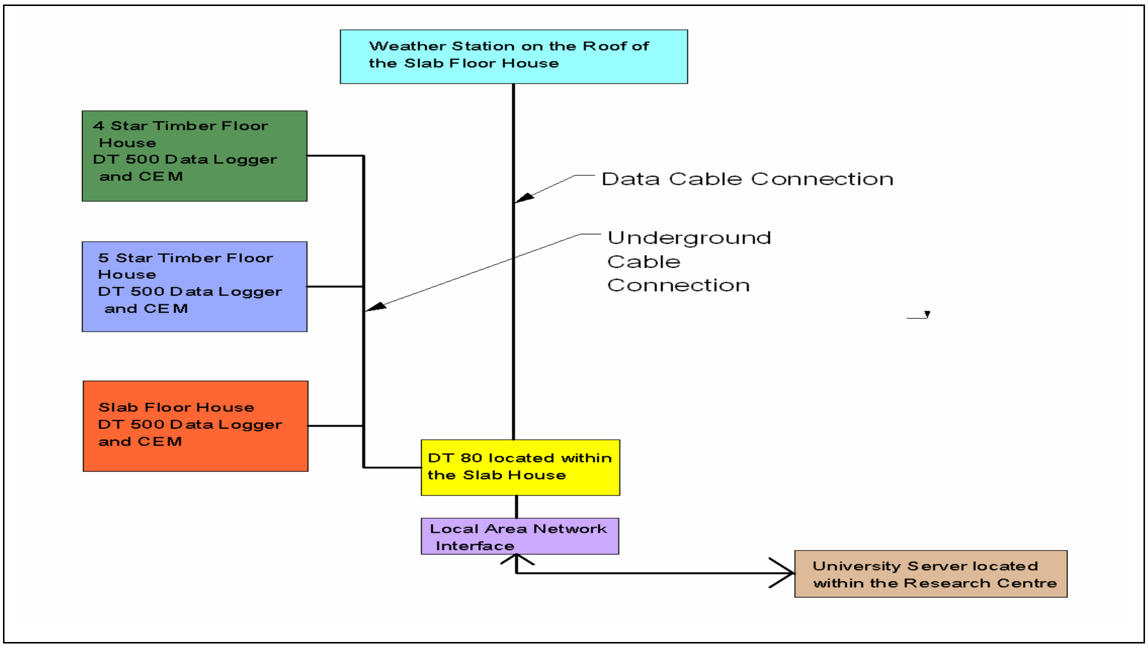


Figure 6.62: Schematic diagram of the Local Area Network connection to the University's server

The cabling method required a two-wire parallel connection between the DT 500 data loggers and the DT 80 data logger, as shown in Figure 6.63. The DT 80 data logger was then connected to the University's Local Area Network with a standard eight-wire data cable. The two-wire cable connecting the DT 500 in the houses to the DT 80 was inserted into a conduit, as shown in Figure 6.63. Figure 6.64 shows the placement of conduit connections between the houses before they were covered by a layer of humus and grass.

Figure 6.63: Inserting the cable into conduit for the DT 500 to DT 80 cable connection

Figure 6.64: Installing the cabling connection between the DT 500 and DT 80

6.6.2. Method of Data Storage

a) Data Logger DT 500

During the first three months there were two data loggers installed in each house. One logger stored the data collected from the permanently installed sensors, while the second logger stored the data from the temporary sensors during the free-running operation of the houses. After the manual downloading of data files in the original De-Transfer format, they were converted into comma separated CSV format and stored on the server of the University research centre.

b) Data Logger DT 80

The acquisition of the weather station data also occurred manually from the DT 80 to a memory device at a fortnightly intervals. The downloading of the data files was completed in the original De-View format and also converted into comma-separated CSV format. The weather data files were also stored on the University research centre's server. Figure 6.65 (below) shows the data acquisition of weather data from the DT 80.

Figure 6.65: Downloading weather data from the DT 80

6.6.3. Data Cleaning

The data cleaning process took six months, commencing in early March 2009 and was completed in late September 2009. As up to seventy sensors were installed in each house, downloading data at 10 minute intervals, the number of files to be cleaned was significant and time-consuming. The data cleaning methods followed the same process as adopted for the test cells in Launceston and were developed in close consultation with CSIRO researchers (Dewsbury 2011). Starting with the raw base data (as acquisitioned from the data logger), a new version of the database was established for each checking and cleaning procedure. For the checking and cleaning step one (V1), the data was checked to see whether or not the temperature was within a predetermined range of measurements. The range of measurements was selected based on an educated assumption of expected measurements within the houses. Data outside the pre-determined range was subjected to further examination and was either adjusted or deleted as appropriate. During the last checking step, version 7 (V7), the data was checked for any unexplainable, unusual, or drastic shifts, fluctuations or patterns.

The actual data checking was undertaken by employees at the School of Architecture and Design’s Centre for Sustainable Architecture with Wood (CSAW). The project researcher was not involved in the data checking process, to allow for independent and objective checking, without the influence of the researcher’s personal engagement and intimate knowledge of the thermal performance of the houses. All enquiries by the data checking team were attended to and their outputs were checked by the project researcher. Technical experts from the University’s School of Engineering and Architecture and Design were engaged to assist with the setting of realistic range and step measurements for all sensor locations in the houses. Additionally, data checking involved cross-comparison, either with data from a nearby sensor or from additional relevant sensors in the weather station. Table 6.3 shows the step-by-step data cleaning process used for this project.

Table 6.4: Method of Data Cleaning of the Test Houses

V1	10 Minute Data Range Checks	Each sensor device was allocated an expected range of measurement. All the data were checked to ensure the measurements were within that range.
V2	10 Minute Data Step Checks	Each sensor device was allocated an expected step value within a 10 minute data reading. All data were then checked to ensure step measurements were within the pre-determined step check range.
V3	10 Minute Data Graphical Checks	Graphical software converted the data into a graphical format. This analysis checked for abnormal shifts or unusual data patterns. Large data swings were analysed and checked.
V4	Averaging 10 Minute Data into Average Hourly Format	The six individual 10 minute reading were averaged to an hourly value. The only exception was the averaging of wind speed and wind direction, which used a different method of establishing hourly values.
V5	Average Hourly Data Range Checks	Each sensor device was allocated an expected range of measurement. All data were checked to ensure the measurements were within that range.
V6	Average Hourly Step Checks	Each sensor device was allocated with an expected step value within an hourly data reading. All data were then checked
V7	Average Hourly Data Graphical Checks	The final checking process was the application of graphical software to convert the data into graphical presentation. This method highlighted abnormal shifts or unusual data patterns.
V8	Average Hourly Data	Specific selected data averaged and used for the empirical validation with AccuRate

In data range step version 1 (V1) a ten-minute range check measurement was allocated to each sensor. This included some investigation and predetermining of realistic environmental measurement fluctuations for both inside and outside sensors. For example, the estimated expected inside roof temperature fluctuation in the 4-star timber floor house was between -3ºC and 50ºC, while the actual measured temperature range was only 0ºC to 35ºC. The project researcher had to accept or reject the measured temperature range, in consultation with experts in the Schools of Architecture and Design and Engineering. In general terms, the estimated environmental measurements of range and step values were within the range of actual measured values.

The graphical checking of data required a different mechanism. Here, a ten minute and an hourly interval data were checked and analysed. Unusual fluctuations, changes in patterns, or drastic spikes and sharp dips, were investigated to determine the validity of the measurements. This often required the checking of other nearby sensors, or the additional investigation of weather patterns occurring at that time. For example, some sensors showed drastic spikes in temperature and only after some further research was it realised that the sensor had been exposed to solar radiation at that particular time. These phenomena occurred in the early mornings to the sensors located in the bedrooms and in the late afternoon to the sensors located in the living room. Figure 6.66 shows a sample of a graphical presentation of temperature gradient in the living room of the 5-star timber floor house during a 5-day period, based on averaged hourly temperature values.

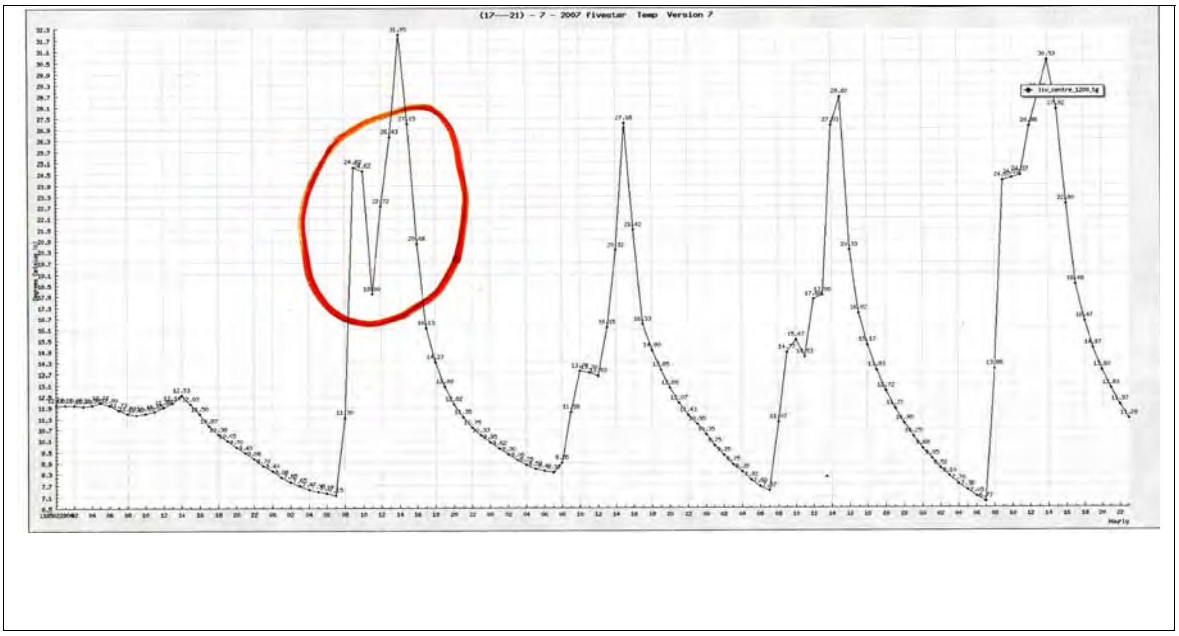


Figure 6.66: Temperature graph for a 5 day interval in the centre of the living room at 1200 height from floor level. Here the dip in temperature on day 2 was investigated

As mentioned above, a sharp dip in temperature at 9 a.m. was questioned by the data checking team. Further examination of the trend of solar radiation showed a distinct dip in the amount of solar radiation at the eastern wall at exactly the same time as the temperature dip in the living room occurred. Figure 6.67 shows the fluctuation of solar radiation at the eastern wall, which explains the pronounced swings in temperature measurements.

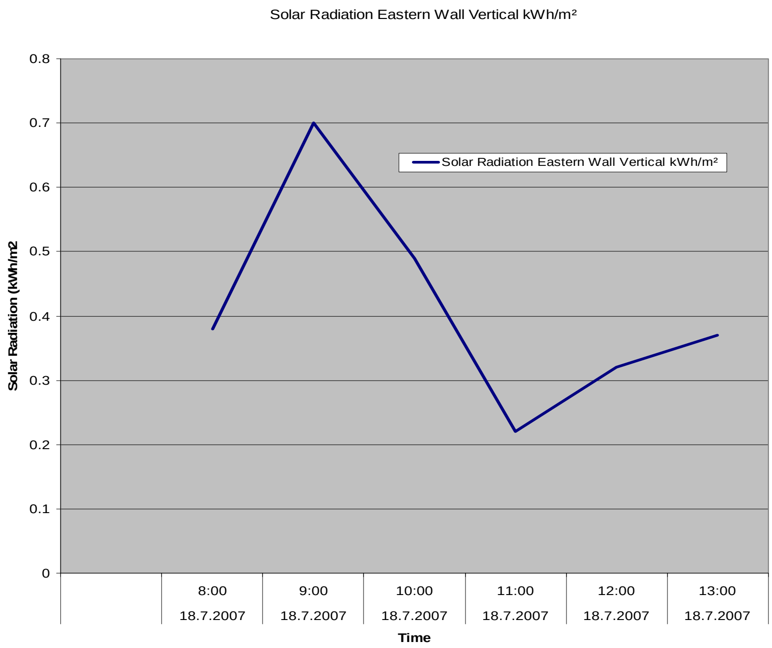


Figure 6.67: Solar radiation received at the eastern wall of the 5-star timber floor house on 18.7.2007 between 8 a.m. and 1 p.m.

The graphical checking of the data and analysis of the unusual temperature fluctuations, spikes and dips showed that all the data was useable, once the reasons for the unusual temperature profiles were fully understood.

6.7. Summary

An extensive range of measurements was collected during the three months of free-running operation of the houses. While only a limited number of measurements was necessary for this validation process, many additional measurements were taken, to provide valuable data backup as well as data for future thermal performance research outside the scope of this study.

Utmost care was taken to ensure the proper installation of cables, plug connectors, sensors and all other measuring devices. Testing of wiring, cables and sensors included an elaborate checking of calibration and mechanisms to ensure the proper functioning of the system. For the purpose of this empirical validation study, environmental measurements for three weeks duration (from 5 September to 26 September) were processed rigorously into a complete data set for comparison with the thermal performance of the houses as simulated by AccuRate. The relevant data files were:

- Roof space dry bulb air temperature;
- 1800mm height at centre of room dry bulb temperature for all rooms;
- 1200mm height at centre of room dry bulb temperature for all rooms;

- 600mm height at centre of room dry bulb air temperature for all rooms;
- Subfloor dry bulb air temperature in the timber floor houses;
- All weather station measurements.

The reliable instrumentation and meticulous data checking and cleaning mechanism resulted in a high quality data set for the empirical validation of the HERS AccuRate. The Chapter 7 focuses on the simulation software AccuRate and describes the appropriate simulation procedures for the empirical validation of AccuRate.

Chapter 7 also illustrates the preparation of AccuRate's input data required for the empirical validation process and explains the thermal simulations of AccuRate.

Chapter 7: AccuRate Thermal Performance Simulations of the Test Houses

7.1. 1 Introduction

Chapter 6 focused on the installation of the monitoring equipment and data acquisition and concluded that a reliable instrumentation and meticulous data checking and cleaning mechanisms resulted in a high quality set for empirical validation of the software AccuRate. Chapter 7 describes the preparation of AccuRate's input data for the empirical validation process and the thermal simulation of AccuRate of the three test houses.

Standard AccuRate simulations serve the purpose of obtaining the required star rating as part of the building approval requirements. These simulations are based on the input data from general building plans and specifications, and the selection of a pre-determined climate zone in which the building is sited. This type of simulation is not suitable for the empirical validation of the software for the following reasons:

- The building fabric input data based on the building plans do not necessarily meet the as-built construction;
- AccuRate's pre-determined climate data might not represent the site climate conditions. Comparison of simulated data and empirical data must be made using specific climate information, that is, measured on-site climate data.

Judkoff (1988) refers to two of the most typical empirical validation errors, namely: differences between the actual weather surrounding the buildings and the weather input used by the simulation program, and the differences between the actual built thermal physical properties of the building, as compared to that assumed for the simulation. He further recommended that for empirical validation the construction input data must fully match the specifications of the as-built construction. Lomas et al. (1997) stated that one of the most important parameters of empirical validation is that the weather data must have been collected at the site of the building. This required a number of modifications to AccuRate's input information and this chapter presents why and how these input parameters were modified.

7.2. AccuRate Simulation for the Purpose of Empirical Validation

The basic reasons for modifying the simulation input data are as follows:

1. The building parameters provided by AccuRate do not include either the effect of thermal bridging in the timber framing or the insulation gaps in the ceiling due to the recessed light fittings;
2. AccuRate's in-built Typical Metrological Year (TMY) climate data do not represent realistic external environmental conditions and are therefore unsuitable for empirical validation. Therefore, measured on-site climate data was used.

Table 7.1 shows the comparison of a standard AccuRate simulation used for a general star rating house assessment and the detailed AccuRate simulation required for empirical validation purposes.

Table 7.1: Comparison of a standard AccuRate simulation and simulation for empirical validation

AccuRate Inputs	Standard AccuRate Simulation (pre-determined data)	AccuRate Simulation for Empirical Validation (measured data)
Building Fabric	Houses as designed and presented on drawings	As-built on building site
Climate data	AccuRate's inbuilt TMY climate file (default setting)	On-site measured climate data

In preparation for the thermal simulations of the test houses, a range of modifications to AccuRate's input data were required as follows:

- Calculating the true values of ceiling and wall insulation, instead of the software's assigned values. The values of insulation were affected by the timber framing ratio and the recessed light fittings in the ceiling of the houses;
- Changing the setting within the software to simulate a free-running operation in lieu of heating and cooling the houses;
- Substituting site-measured infiltration values for AccuRate's in-built values;
- Deleting the heating and cooling load settings to simulated free-running operation. As the houses were not occupied during the free running-operation, no electrical heating and cooling took place in the houses and no electrical appliances were used;

- Changing the window input settings to a closed window position during the free-running operation. In addition, no window coverings were drawn during night time. AccuRate asks for a certain percentage of window openings based on the type of windows. This information is then used in the simulation for the cooling requirements, automatically opening the windows if the temperature in the rooms exceeds a pre-set temperature. AccuRate simulation also assumes mandatory window coverings (Holland blinds). As no window coverings were used during the free-running operation, the houses were simulated without the use of window coverings;
- Calculating window framing ratio based on as-built condition, instead of the in-built AccuRate window frame values;
- Using site-measured climate data instead of AccuRate's in-built TMY climate file.

The first part of this chapter describes how the modified inputs were determined. The second part compares climate data for simulated and measured values. The chapter concludes with a general description of AccuRate's output data.

7.3. AccuRate Simulation Inputs

The AccuRate software was developed over many years by the CSIRO in Australia. A brief history of its development is given in Chapter 2. The standard AccuRate inputs are:

- Selecting the postcode for the project's location, thereby linking the postcode to the appropriate climate file;
- Describing all zone types and zone volumes;
- Defining construction elements, including: walls, ceiling, floor, roof and windows;
- Designating external shading features, such as adjacent trees or buildings;
- Selecting orientation of the building for the purpose of infiltration calculation;
- Simulating the free-running operation of the houses (that is: no heating and cooling requirements).

The non-standard input data which can be modified to account for the as-built /on site climate condition are as follows:

- The buildings fabric insulation value to account for thermal bridging of the timber framing (framing factor) and insulation gaps in the ceilings left around the recessed light fittings;
- Infiltration values;

- Window framing ratio;
- On-site climate data in lieu of AccuRate's default climate file.

AccuRate simulation requires various input data to provide the thermal performance prediction for a building. Some of the standard input data were easily modified for the specific project requirements; however, some of the non-standard inputs were not easily modified because they required more detailed calculation and analysis. For the purpose of empirical validation, the modification of the non-standard input data was imperative. The non-standard modifications involved changes to AccuRate's scratch file and will be described in Section 7.4.

7.3.1. Exposure and Ground Reflectance

When a new project file is created in AccuRate, the project data screen asks for general project details including the entry of the postcode, for example: Hobart, 7000. With Hobart's postcode, the corresponding climate zone 26 was automatically designated. Two important input data entry requirements are: Exposure and Ground Reflectance. The AccuRate help file defined the different types of exposure as follows:

- Exposed: Flat open country with few or no trees or buildings (this should rarely occur);
- Open: Normal countryside with some trees and scattered buildings;
- Suburban: Low rise built-up areas in the suburbs of towns and cities;
- Protected: High density inner city or CBD, with tall buildings nearby.

The selected exposure for the simulation of the three houses was selected as 'suburban'.

The AccuRate help file defined the ground reflectance as follows: 'The proportion of solar radiation that is reflected by the ground immediately adjacent to the building' (AccuRate help file).

The project data screen shows the necessary input data needed to simulate the ground reflectance of the building. The input ranged from 0 to 1, with the setting default value of 0.2, corresponding to a grassed surface around the building. As the houses on the southern side are surrounded by a light grey concrete driveway and grassed area around the remaining sides, a 0.5 value for the ground reflectance was chosen, taking into account the higher ground reflectance off the light coloured concrete driveways.

7.3.2. Construction Data

The construction details of the external building fabric and internal walls were entered into the AccuRate construction master input table. The individual fabric elements were selected from AccuRate's materials' library. The construction input data were chosen with meticulous attention to detail.

The conductivity values of individual building members of the as-built external wall and ceiling required additional analysis. The timber framing is part of the insulation fabric in a standard brick veneer wall, but AccuRate's simulation does not recognise the much higher conductivity value of the timber framing as compared to the insulation materials (Belusko 2008). Similarly, the ceiling and wall insulation were modified to account for the much higher conductivity values of the timber framing. In addition, AccuRate simulations do not account for the required insulation gaps around recessed ceiling light fittings: therefore, further modifications to the ceiling insulation values were made and described in detail in the following section (Chen 2010, pers. comm. 4 July). The USA's California Energy Commission assumes an average framing factor of 27% and ASHRAE (2003) reported an average framing factor of 25% for residential buildings. However, Bell & Overend (2001) have documented framing factors of up to 40% in the UK.

a) The Framing Ratio and Insulation Values

The framing ratio represents the fraction of the total building component area that is used by the framing material. Most houses in Australia consist of timber or steel framing, used for the wall, floor and roofing structure. For example, in timber-framed walls, the general stud spacing occurs at 450mm centres with one horizontal nogging framed between the individual studs. Other framing includes: top and bottom plate and lintels over window and door openings. The framing structure is often in contact with the exterior skin of the building fabric and presents a distinctive break in the insulation values of floors, walls and ceilings. This is shown in Figure 7.1, where the 83mm rockwool insulation represents an R-value of 2.5m²K/W, (conductivity k = 0.033), while the 90mm hardwood studwork frame corresponds to an R-value of only 0.53m²K/W (conductivity k = 0.17).

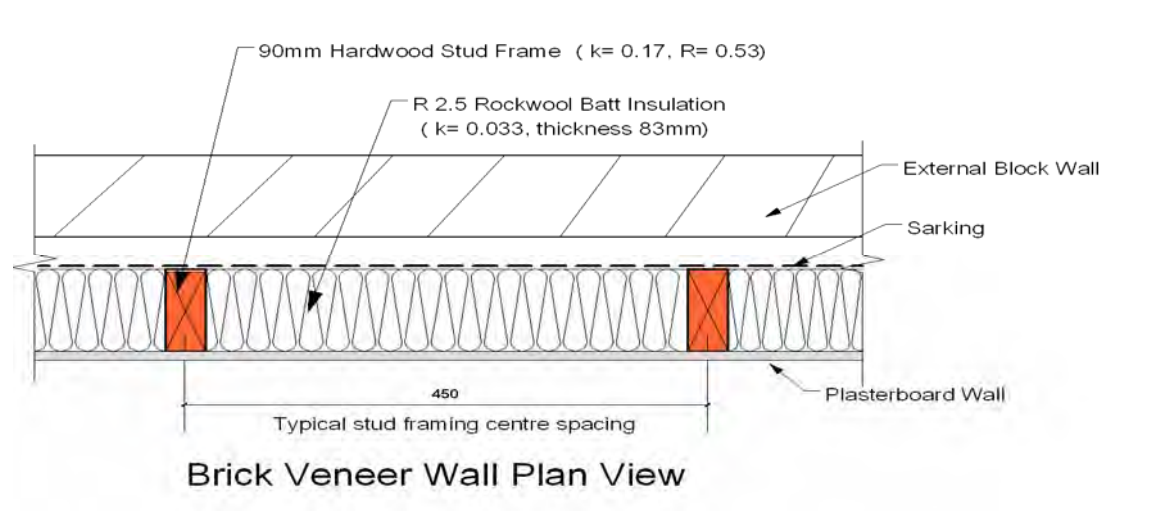


Figure 7.1: Typical brick veneer wall with 90mm stud framing spaced at 450mm centres

Two important steps were necessary to determine the value of the framing factor, namely:
Step 1, the timber wall-framing area within a wall area was quantified and the corresponding insulation values for the whole wall were calculated. Step 2 involved the determination of the revised insulation thickness and the modification of the building fabric input data into AccuRate's construction master table. The Figure 7.2 (below) shows an insulated wall section of the test house in Kingston, including the installed rockwool insulation between the timber studs of the wall.

Figure 7.2: Timber framing of the test house showing the ratio of studwork as part of the whole wall

b) Methods for Calculating the Framing Ratio

ASHRAE (2009) describes two methods of establishing the average resistance of a building section, namely:

- The parallel-path method;
- The isothermal-planes method.

Using the parallel path method, the total R-value for each building section, (one containing the framing material and one containing the insulation) is calculated. The average R-value of the building area is then calculated using the fractional area of the framing and the insulation. Table 7.2 shows sample calculations using the parallel-path method applied to a brick veneer wall with a resulting timber framing ratio of 0.24.

Table 7.2: Parallel-path calculation method (Source ASHRAE 2009)

Element	R-Value of insulated wall section (m^2K/W)	R-Value of framed wall section (m^2K/W)
OS surface (24km/h wind)	0.03	0.03
Brick wall	0.18	0.18
Reflective cavity	0.28	0.28
R 2.5 insulation	2.50	
90 Hardwood Timber Stud (k=0.17)		0.53
10 Plaster board	0.06	0.06
IS surface (still air)	0.12	0.12
Total R-Value	3.15	1.20
U=1/3.15 and U = 1/1.23	0.317	0.833
	76%	24%

$$U_{av} = (0.76 \times 0.317) + (0.24 \times 0.833) \quad \text{Equation 7.1}$$

$$U_{av} = 0.441 W/m^2K$$

$$R_{t(av)} = 1/0.441 m^2K/W$$

$$R_{t(av)} = 2.268 m^2K/W$$

Normally, the AccuRate simulation would have assigned the R-value of 3.15 m^2K/W for the brick veneer wall fabric as input data, whereas when calculating the hardwood framing ratio of 0.24, the R-value is reduced to 2.268m^2K/W, indicating a significant reduction of 28%.

Using the isothermal-planes method, the fractional areas were applied only to the building layer that contains the timber studs and the insulation between the studs. The average R-value for this layer was than added to the R-value for the overall building section to obtain the total average R-value for the wall area. The following sample of the isothermal-planes method was applied to a brick veneer wall with a framing ratio of 0.24.

The average R-value for the timber stud and insulation layer of the building section was calculated using the fractional areas of timber studs and insulation,

$$U_{av} = 0.76 \text{ x } (1/2.5) + 0.24 \text{ x } (1/0.53) \quad \text{Equation 7.2}$$

$$U_{av} = 0.757 \text{ W/m}^2\text{K}$$

$$R_{av} = 1/0.757 \text{m}^2\text{K/W}$$

$$R_{av} = 1.321 \text{m}^2\text{K/W}$$

Table 7.3: Isothermal-planes calculation method (Source ASHRAE 2009)

Element	R-Values (m^2K/W)
OS Surface (24km/h wind)	0.030
Brick wall	0.180
Reflective cavity	0.280
R_{av} for studs and insulation based on 0.24/0.76 ratio	1.321
10 Plaster board	0.06
IS surface (still air)	0.12
$R_{t(av)}$	**1.991**

In this case the initial R-value of the brick veneer wall of 3.15m²K/W was now reduced to 1.991m²K/W as a result of the framing ratio, representing a significant reduction of 37%.

The isothermal method was adopted to calculate the revised wall and ceiling insulation value of the test houses. This method is deemed to calculate more correctly the total resistance value of a wall assemblage. Firstly, it calculates the revised R-value for the area of wall where the bridging element occurs and secondly, it establishes a mathematical method of calculating a revised total resistance value for the building elements.

c) Establishing the Test Houses Framing Ratio for External Walls

Determining the framing ratio for the test houses required the calculation of the area of wall and ceiling framing. A scale drawing of the floor plan and 16 individual wall-elevations (showing the exact framing layout) were produced with the assistance of site photographs taken at the construction stages. Figures 7.3 to 7.6 show sample photographs that were used to establish the wall elevation drawings.

Figure 7.3: Corner detail of the framing stage of the test house

Figure 7.4: Framing stage of the test house

Figure 7.5: Completed wall-framing stage of the test house

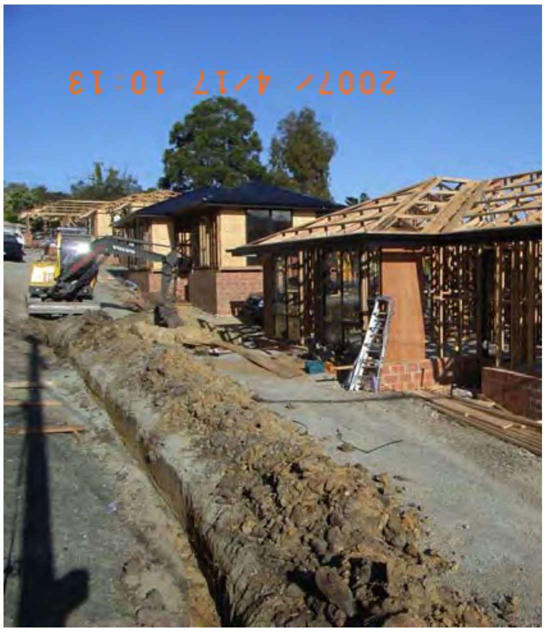


Figure 7.6: Framing stage of the concrete slab test house

Figure 7.7 depicts the elevation of the wall-framing of the houses used for calculating the wall framing ratio.

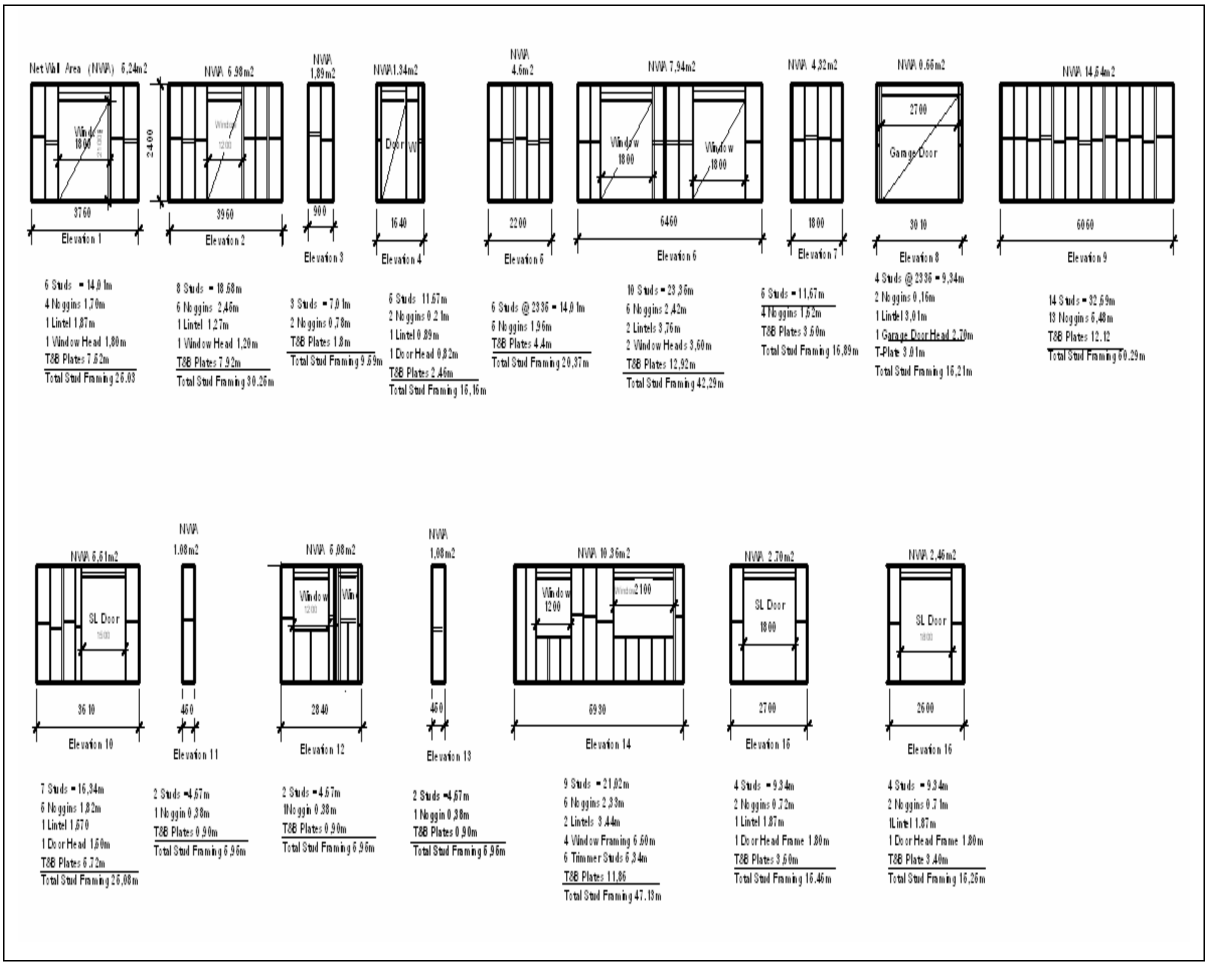


Figure 7.7: Elevation of external views of wall framing of the test houses

The exact wall-framing ratios for the test houses were calculated as shown on Table 7.4.

Table 7.4: Calculating the wall framing factor for 12 individual wall elevations

Elevation	Tot Length of all Studs (m)	Stud Width (m)	Stud Area (m2)	Lintel Length (m)	Lintel Width (m)	Lintel Area (m2)	Timber Area (m2)	Wall Area (m2)	Framing Ratio
1	25.03	0.035	0.876	1.876	0.19	0.35	1.23	5.24	0.23
2	30.25	0.035	1,059	1.27	0.15	0.19	1.25	6.98	0.18
3	9.59	0.035	0.336				0.336	1.89	0.17
4	15.16	0.035	0.531	0.890	0.15	0.134	0.665	1.34	0.49
5	20.37	0.035	0.713				0.713	4.60	0.16
6	42.29	0.035	1.480	3.76	0.19	0.714	2.194	7.94	0.28
7	16.89	0.035	0.591				0.591	4.32	0.14
8	15.21	0.035	0.532	3.01	0.25	0.753	1.285	0.65	1.98
9	50.29	0.035	1.760				1.760	14.54	0.12
10	25.08	0.035	0.878		0.15	0.236	1.114	5.51	0.20
11	5.95	0.035	0.208				0.208	1.08	0.18
12	30.88	0.035	1.081	1.94	0.15	0.291	1.372	5.08	0.27
13	5.95	0.035	0.208				0.208	1.08	0.18
14	47.13	0.035	1.650	3.44	0.19	0.653	2.303	10.36	0.22
15	15.46	0.035	0.541	1.87	0.19	0.355	0.896	2.70	0.33
16	15.25	0.035	0.534	1.87	0.19	0.355	0.889	2.46	0.36
						Total	**17.01**	**75.47**	**0.23**

d) Calculating the Test Houses' Revised Wall Insulation using the Isothermal-Planes Method

The average R-value for the timber studs and wall insulation area were calculated as follows:

5-star timber floor and slab house:

$$U_{av} = 0.77 \text{ x } (1/2.5) + 0.23 \text{ x } (1/0.53) \qquad \text{Equation 7.3}$$

$$U_{av} = 0.742 W/m^2K$$

$$R_{av} = 1/0.742 m^2K/W$$

$$R_{av} = 1.347 m^2K/W$$

4-star timber house:

$$U_{av} = 0.77 \text{ x } (1/1.5) + 0.23 \text{ x } (1/0.53) \qquad \text{Equation 7.4}$$

$$U_{av} = 0.948 \text{ } W/m^2K$$

$$R_{av} = 1/0.948 \text{ } m^2K/W$$

$$R_{av} = 1.05 m^2K/W$$

The final R-value for the entire wall section was now established, as shown in Table 7.5.

Table 7.5: Isothermal method to establish revised wall insulation

Element	R-Value 4-star timber floor house (m^2K/W)	R-Value 5-star timber floor and slab floor house (m^2K/W)
OS Surface (24km/h wind)	0.030	0.030
Brick wall	0.180	0.180
Reflective cavity	0.280	0.280
R_{av} for studs and insulation based on 0.23/0.77 ratio	**1.05 revised R-value for AccuRate input**	**1.35 revised R-value for AccuRate input**
10 Plaster board	0.06	0.06
IS surface (still air)	0.12	0.12
$\mathbf{R_{t(av)}}$	1.72	2.016

Considering the wall-framing ratio of 0.23, the average total R-Value for the 5-star timber floor and slab floor house wall fabric was reduced to R 2.016m^2K/W, which is 36% less than the default setting in AccuRate's original R-value of 3.15m^2K/W for a brick veneer wall, which included an added R 2.5 insulation between the studwork.

e) Establishing the Test Houses' Ceiling Framing Ratio and Revised Value of Ceiling Insulation

The area of the ceiling-framing was calculated to establish the ceiling framing ratios. In order to calculate the area of ceiling-framing, a scaled ceiling-framing diagram was drawn indicating all ceiling timber members, as shown in Figure 7.8.

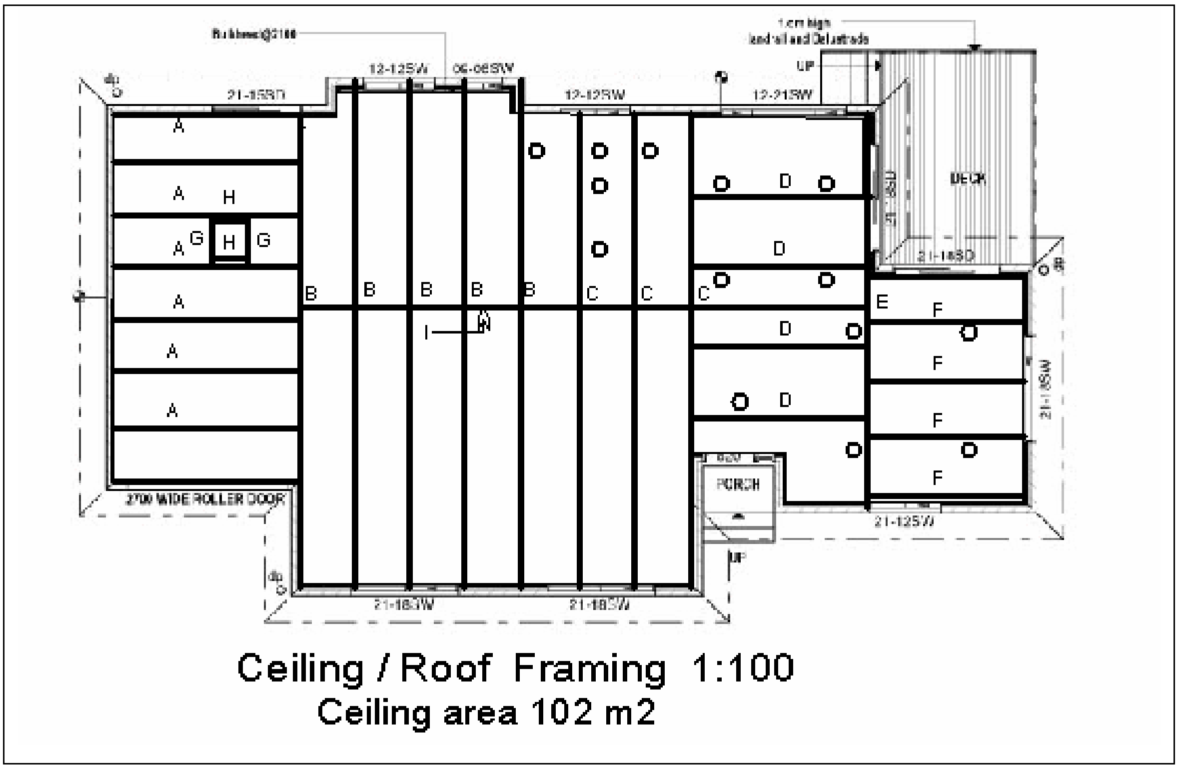


Figure 7.8: Diagram of the ceiling-framing layout

All the ceiling members, including the individual lengths and areas, are calculated in the following Table 7.6.

Table 7.6: Calculating the area and framing ratio of ceiling-framing

Member	Quantity	Individual Length (m)	Total Length (m)	Width (m)	Area (m^2)
A	8	3.05	24.40	0.035	0.85
B	5	8.56	42.80	0.035	1.50
C	3	8.00	24.00	0.035	0.84
D	4	2.95	11.80	0.035	041
E	1	4.10	4.10	0.035	0.14
F	4	2.75	11.00	0.035	0.39
G	2	0.86	1.72	0.035	0.06
H	2	0.60	1.20	0.035	0.04
I	1	9.50	9.50	0.035	0.33
			Total Ceiling Area 98.2m^2	**Total Timber Area**	**4.56**
				Framing Ratio	**0.046**

The revised R-value for the ceiling, based on a 0.046 framing ratio, the average R-value for the timber area and insulation, are calculated as follows:

5-star timber floor and slab floor house:

$$U_{av} = 0.954 \text{ x } (1/4.0) + 0.046 \text{ x } (1/0.53) \qquad \text{Equation 7.5}$$

$$U_{av} = 0.326\text{W/m}^2\text{K}$$

$$R_{av} = 1/0.326\text{m}^2\text{K/W}$$

$$R_{av} = 3.07\text{m}^2\text{K/W}$$

4-star timber floor:

$$U_{av} = 0.954 \text{ x } 1/3.5) + 0.046 \text{ x } (1/0.53) \qquad \text{Equation 7.6}$$

$$U_{av} = 0.36\text{W/m}^2\text{K}$$

$$R_{av} = 1/0.36\text{m}^2\text{K/W}$$

$$R_{av} = 2.78\text{m}^2\text{K/W}$$

Table 7.7: Isothermal Method to establish revised ceiling insulation

Element	R-Value 4-star floor house (m^2K/W)	R-Value 5-star floor and slab house (m^2K/W)
OS Surface	0.030	0.030
R_{av} for ceiling joists and insulation (based on 0.954/0.046 ratio)	2.78	3.07
10 Plasterboard	0.06	0.06
IS surface (still air)	0.12	0.12
$R_{t(av)}$	2.99	3.28

The revised R-value for the 5-star timber floor and slab house ceiling is 23% less than the default setting of AccuRate's ceiling insulation value of 4.31m²K/W.

f) Reduced Ceiling Insulation due to the Recessed Ceiling Light Fittings

As discussed in Chapter 5, fourteen recessed quartz halogen downlights were installed in the ceiling of the kitchen/dining/living area. Downlight covers installed over the recessed light fittings would have allowed the insulation to be installed flush to downlight covers up to 50mm in height, and then tapered off to the original depth. However, even with the downlight covers, the electrician insisted on a 200mm insulation gap around the light fittings, as shown in Figure 7.9, in compliance with AS 3000.

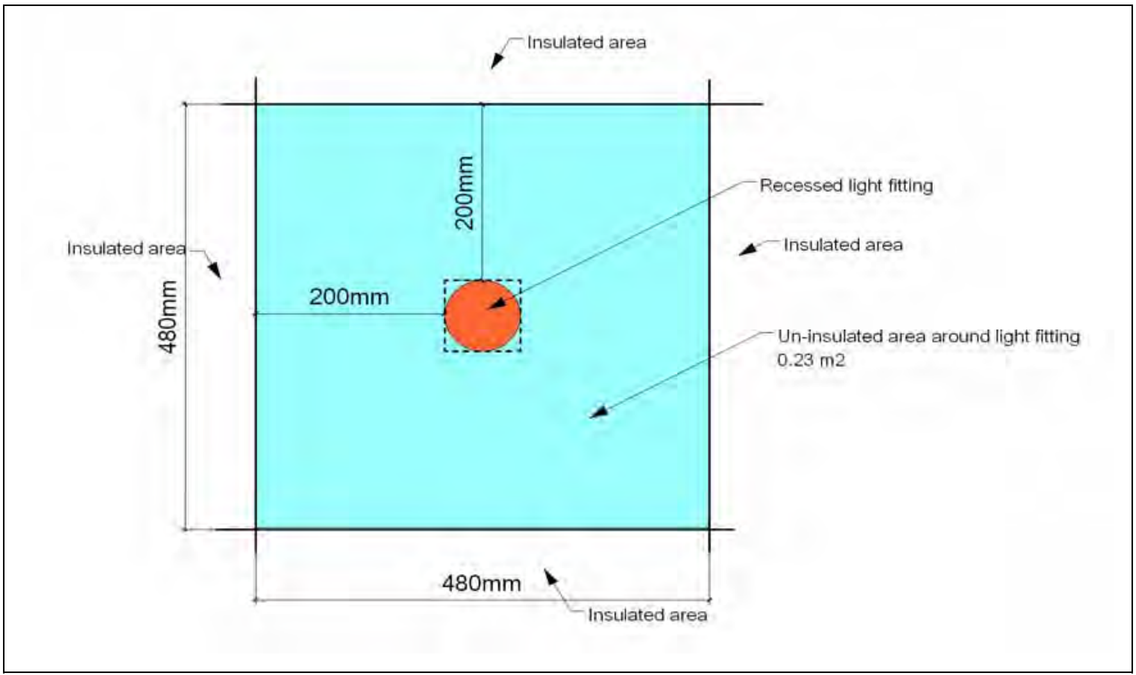


Figure 7.9: Diagram showing an uninsulated area around recessed light fittings in the test houses, as installed by the electrician to AS 3000

Figure 7.10 shows the thermal image of a typical downlight, with the blue area around the light fitting clearly indicating the cold parts of the un-insulated area. Figure 7.11 shows the downlight installed in the ceilings of the houses.

Figure 7.10: Thermal image of the recessed downlight and gap of insulation around the light fitting

Figure 7.11: Photo of recessed downlight fittings installed in the test houses

The gaps around the fourteen installed downlights left an uninsulated ceiling area of 3.23m², hence further decreasing the insulation value of the ceiling. Considering a ceiling size of 98.2m², the uninsulated area of 3.23m² represents a ratio of 0.03. The revised R-value of the ceiling was calculated using the isothermal method.

For the 5-star timber floor and slab house:

$$U_{av} = 0.97 \text{ x } (1/3.07) + 0.03 \text{ x } (1/0.21) \qquad \text{Equation 7.7}$$

$$U_{av} = 0.463 W/m^2K$$

$$R_{av} = 1/0.463 m^2K/W$$

$$R_{av} = 2.15 m^2K/W$$

For the 4-star timber floor house:

$$U_{av} = 0.97 \text{ x } (1/2.78) + 0.03 \text{ x } (1/0.21) \qquad \text{Equation 7.8}$$

$$U_{av} = 0.492 W/m^2K$$

$$U_{av} = 1/0.492 m^2K/W$$

$$R_{av} = 2.03 m^2K/W$$

The revised R-value for the ceiling value is presented in Table 7.8.

Table 7.8: Isothermal Method to establish revised ceiling insulation

Element	R-Value 4-star timber floor house (m²K/W)	R-Value 5-star timber floor and slab floor house (m²K/W)
OS Surface	0.030	0.030
R_{av} for ceiling insulation and gaps of insulation around 14 recessed light fittings (based on 0.97/0.03 ratio)	2.03 revised R-value for AccuRate input	2.15 revised R-value for AccuRate input
10 Plaster board	0.06	0.06
IS surface (still air)	0.12	0.12
$R_{t(av)}$	2.24	2.36

Considering the initial ceiling batt insulation value of 4.0m²K/W in the 5-star timber and slab house, (default setting over the entire ceiling area) the final ceiling insulation value was reduced to R 2.15m²K/W, due to the framing ratio and insulation gaps around the light fittings, indicating a significant reduction of 46.2%. Table 7.9 provides a summary of the reduced R-values of the ceiling insulation, due to the framing factor and the installation of recessed downlights.

Table 7.9: Summary of reduction of ceiling insulation value due to framing ratio and installation of downlights for the test house

Elements	4-star timber floor house (m²K/W)	4-star timber floor house revised (m²K/W)	5-star timber floor and slab house	5-star timber floor and slab house revised
Wall- framing ratio	1.5 (AccuRate initial input)	**1.05** (framing ratio 23%)	2.5 AccuRate initial input	**1.35** (framing ratio 23%)
Ceiling -framing ratio	3.5 (AccuRate initial input)	2.81 (framing ratio 4.4%)	4.0 AccuRate default	3.11 (framing ratio 4.4%)
Ceiling insulation gaps around light fittings	From 2.81 to ⟶	**2.03**	From 3.11 to ⟶	**2.15**

g) Establishing Thickness of Insulation

The revised thicknesses of wall and ceiling insulation, based on the revised R-values, were entered into AccuRate's external wall and ceiling construction input file. The revised thickness of wall and ceiling insulation was calculated by multiplying the revised R-value of insulation by the conductivity of the insulation material (thickness of insulation = conductivity x R-value). Table 7.10 and 7.11 summarise the calculation of the revised insulation thickness of walls and ceiling for the 4-star timber floor house, the 5-star timber floor and slab floor house.

Table 7.10: Calculation of required thickness, based on revised R-values for wall and ceiling insulation for the 4-star timber floor house

Building Element	Conductivity (k) Source AccuRate Material Selector	Thickness = Conductivity x R-Value	Thickness
Wall insulation initially entered R 1.5 (66mm)	0.044 (fibreglass batts 12 kg/m³))	0.044 x 1.05	**46mm**
Ceiling insulation initially entered R 3.5 (154mm)	0.044 (fibreglass batts 12 kg/m³)	0.044 x 2.03	**89mm**

Table 7.11: Calculation of required thickness based on revised R-values for wall and ceiling insulation for the 5-star timber floor and slab house

Building Element	Conductivity (k) Source:AccuRate Material Selector	Thickness = Conductivity x R-Value	Thickness
Wall insulation initially entered R 2.5 (83mm)	0.033 (rockwool batts)	0.033 x 1.35	**45mm**
Ceiling insulation initially entered R 4.0 (176mm)	0.044 (fibreglass batts $12kg/m^3$)	0.044 x 2.15	**95mm**

7.3.3. Windows in Continuously Closed Position

During the free-running stage, all windows remained in the closed position. The AccuRate program input requests the percentage of window openings in the selected windows column. The openable area for the windows is used to calculate cooling ventilation requirements when indoor temperatures exceed a pre-set temperature. All the openable window areas were set to zero, replicating the free-running mode of the houses with the shut windows. In addition, during the free-running operation no indoor window coverings were drawn and this was reflected in the AccuRate setting by selecting ‘no window coverings’ in the window data input file.

7.3.4. Zero Auxiliary Heating and Cooling Requirements

No auxiliary heating or cooling requirement was necessary during the free running operation of the houses. Simulating this condition with AccuRate was achieved by setting the simulation to a ‘Non-Rating’ mode in the AccuRate’s manager screen and de-selecting the heating and cooling requirement for the individual zones for the kitchen/dining/living area and the bedrooms in the zone’s master table. In addition, the kitchen/dining/living zone and the bedroom zone were classified as ‘all other daytime zones’, automatically eliminating all internal sensible and latent heat gains.

7.4. Modification of AccuRate’s Scratch File

The amendment of non-standard input data occurred within AccuRate’s scratch file. In addition, a specially prepared project climate file was used for the empirical validation in lieu of AccuRate’s original in-built TMY climate data. The project climate file consisted of 3 months of site measured climate data (5 September to 26 September 2007) with the remaining climate data for the year 2007 provided by the Bureau of Meteorology weather station at Ellerslie Road, Hobart.

The AccuRate scratch file is normally not accessed or modified in general house energy rating processes. The scratch file is produced by the software after activating the check button at the end of the simulation entry data process. Once the scratch file is produced, detailed thermal simulation can occur resulting in the assembly of the house energy star rating report, temperature, and energy and output files. The non-standard input data included the following items:

- Modified infiltration values from default settings to site measured values;
- Modified window-framing ratios adjusted to site measured values;
- The use of on-site measured climate data in lieu of AccuRate's TMY in-built climate file.

7.4.1. Modification to Air Change Rates

As stated in Chapter 6, the measurement of infiltration losses in the three houses was conducted by the Mobile Architecture & Built Environments Laboratory (MABEL). In AccuRate the infiltration rate, in air changes per hour, is specified as (Delsante 20050):

$$A + B \times v \quad <1\text{m/s} \qquad \text{Equation 7.9}$$

$$A + B \times \sqrt{v} \quad >1\text{m/s} \qquad \text{Equation 7.10}$$

where A = Air change per hour

B = Wind reduction factor

v = wind speed per hour, multiplied by the terrain factor

Values for A and B were calculated based on MABEL's measured infiltration data report (Luther 2008) and are shown in Table 7.12, together with AccuRate's default values.

Table 7.12: AccuRate's default values and measured values for air change per hour (value A) and wind speed variables (B)

House Type	AccuRate Default Value A	AccuRate Default Value B	Measured Value A	Measured Value B
Slab Floor House Roof Zone	2.00	1.00	1.60	0.07
Slab Floor House Kitchen/Dining/Living	1.07	0.09	0.55	0.00
5-Star Timber Floor House Roof Zone	0.44	0.80	1.17	0.00
5-Star Timber Floor House Kitchen/Dining/Living	0.60	0.12	0.45	0.04
4-Star Timber Floor House Roof Zone	2.00	1.00	0.73	0.16
4-Star Timber Floor House Kitchen/Dining/Living	0.60	0.12	0.35	0.04

The wind speed in AccuRate's weather file data is measured at the local airport at a height of 10m above the ground. To obtain the relevant site wind speed, the measured site wind speed was multiplied by a reduction factor. The wind speed reduction factor of 1.73 was calculated based on the site wind speed measuring device at a height of 5.5m within a suburban location (D Cheng 2010, pers. comm.11 January). The calculated values for A and B were modified in AccuRate's scratch file for the interior rooms (with the exception of the garage) and the roof space for the simulation of the as-built condition of the houses. Figure 7.12 shows a sample of the original in-built data for the value A (air change per hour) and value B (wind speed variable) in AccuRate's scratch file.

```
C Name, volume, infiltration data, wind speed reduction factor, type, SHG di
fractions
C                    Name    Vol      A      B WsRed   Type  EstSG
  3  4   Kitchen/Dining/   88.8   1.07   0.09  0.50Normal      1
```

Figure 7.12: Original AccuRate's scratch file data for values A and B

MABEL's measured infiltration data was used as the basis to modify the wind speed data in AccuRate' scratch file as shown in Figure 7.13.

```
C Name, volume, infiltration data, wind speed reduction factor, type, SHG dis
fractions
C                    Name    Vol      A      B WsRed  Type EstSG
  3  4   Kitchen/Dining/  88.8  0.55  0.00  0.50Normal      1
```

Figure 7.13: Modified wind speed data for the kitchen/dining area of the slab floor house

Figure 7.14 shows similar hourly air change rates for the kitchen/dining/living area and the roof space of the houses, with the slab floor house showing the lowest infiltration rate, with wind speeds over 3m/s. The roof infiltration rates measured in the roof spaces were in contrast to the star ratings, where the 4-star timber floor house exhibited the least air leakage, with wind speed over 1.5m/s and the concrete slab floor house roof space indicates the greatest leakage with wind speed up to 5.5m/s. With wind speed over 5.5m/s the roof space of the 5-star timber house shows the highest infiltration rate. The roof space of the 4-star timber house indicates the lowest infiltration rate, with wind speed above 1.5m/s. The differences of air change rate are due to the variant construction finishes of the houses.

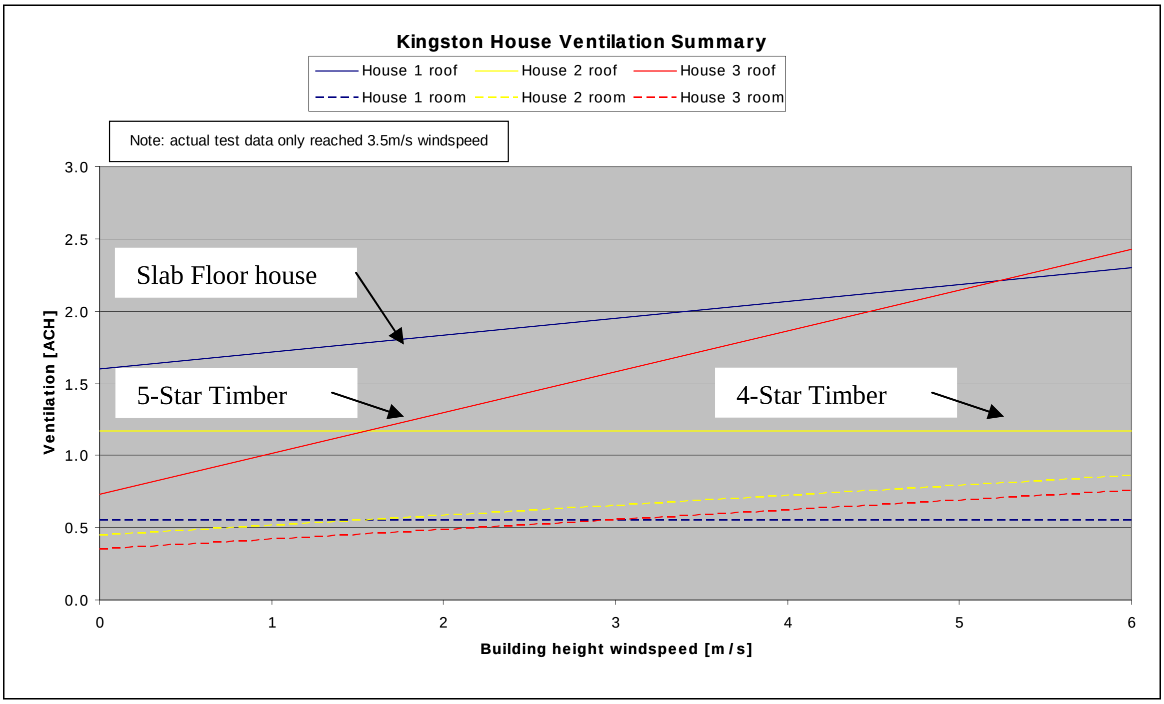


Figure 7.14: Summary of air change rates in the roof space and kitchen/dining/living area for various wind speeds for the houses. (house 1 represents the slab floor house, house 2 the 5-star timber floor house and house 3 the 4-star timber floor house)

7.4.2. Window Framing Ratio

AccuRate's scratch file also contains the construction data for windows, including specifying the proportion of the window system occupied by the frame. The actual values were calculated based on measured data and then modified in AccuRate's scratch file. Figure 7.15 and 7.16 show the window framing details at the houses.

Figure 7.15: Window frame detail for the bedroom window at the 5-star timber floor house

Figure 7.16: Close up of window framing detail

Table 7.13 shows the comparison of AccuRate's in-built window framing ratios and the measured window framing ratios, demonstrating a significant difference for the sliding doors located in the kitchen/dining/living area. As a result of this finding, AccuRate's in-built value of 0.23 was modified to the measured value of 0.17.

Table 7.13: Comparison of AccuRate's in-built window framing ratios and measured window framing ratios for the houses

Window Location	In-built Window Framing Ratio	Measured Window Framing Ratio
Laundry Sliding Door (Single Glazed)	0.17	0.15
Bedrooms, Bath and WC Windows (Single Glazed)	0.15	0.14
Kitchen/Dining/Living, Sliding Doors (Double Glazed)	0.23	0.17
Kitchen/Dining/Living Windows (Double-Glazed)	0.20	0.17

The window framing ratios were modified in AccuRate's scratch file from the in-built settings to the measured values. However, only the window and sliding door framing ratio values were adjusted in the window scratch file data and no window data was changed.

7.5. The Climate Files

The accuracy of the climate data used for thermal simulations of the buildings is one of the most important aspects for achieving realistic simulation predictions. For this project, four different climate files were used, namely:

- AccuRate's original in-built climate file (TMY);
- Bureau of Meteorology (BOM) climate file from Ellerslie Road, Hobart, for the year 2007;
- On-site measured climate file data for three months during free-running operation of the houses, (5 July 2007 to 26 September 2007);
- Project climate file for validation purposes, consisting of: a combination of on-site climate data for the three months free-running stage and the BOM climate data for the remaining year 2007.

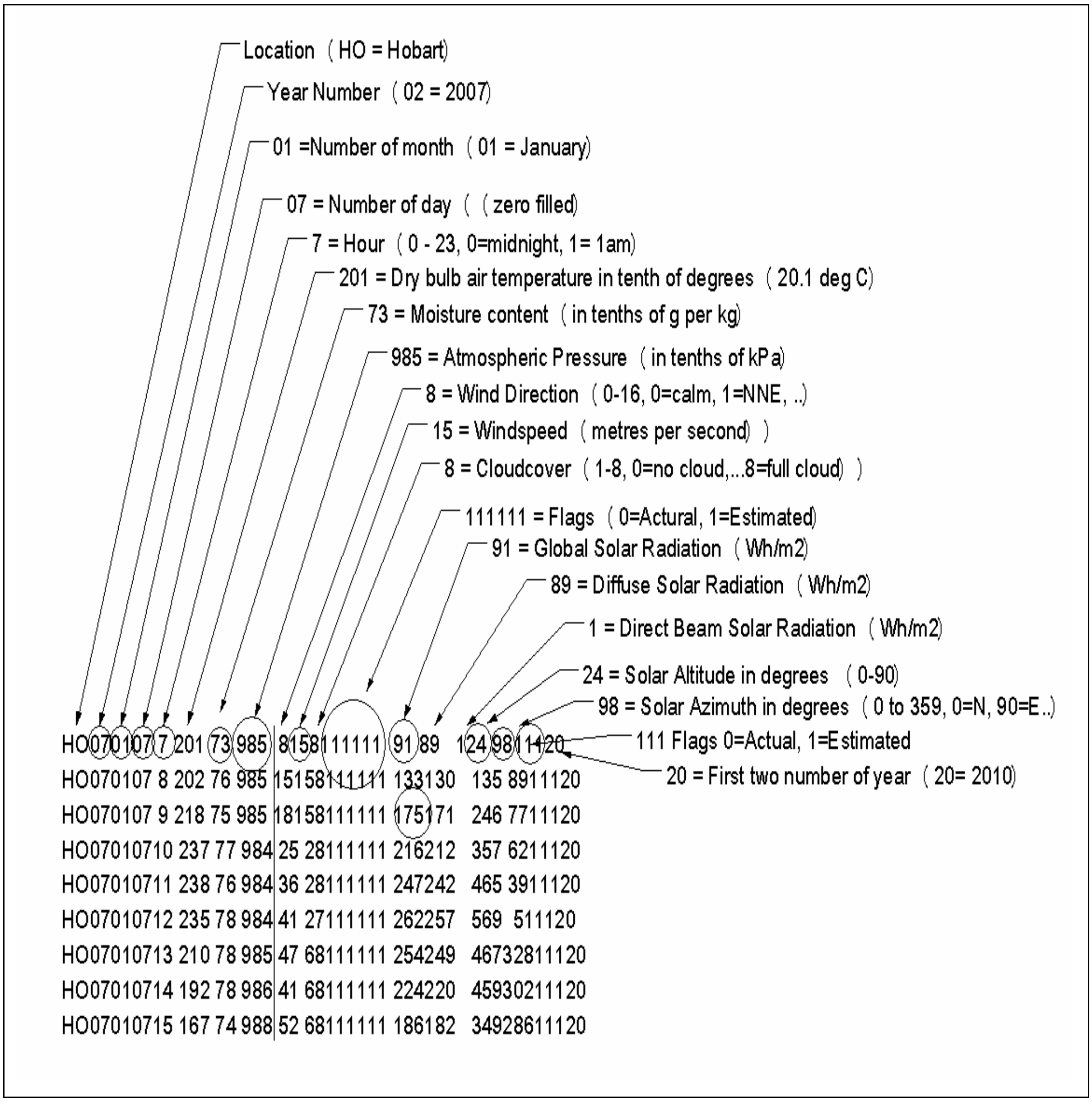
It was necessary to provide one year of climate data, as the software requires a full year of data in order to run.

7.5.1. AccuRate In-Built TMY Climate File

There are 70 different climate files within AccuRate and they were developed for 70 climate zones in various different locations in Australia, from many years of specific data from the Bureau of Meteorology.

AccuRate's Typical Meteorological Year (TMY) climate data represents averaged values over many years and are used in AccuRate for star rating purposes. However, for empirical validation, the AccuRate's in-built climate file is unsuitable, as variations of temperatures up to 7.0ºC were reported between the AccuRate climate file and the measured data (Dewsbury 2011). Therefore, a project climate data file was set up and will be described in the following section. An original AccuRate in-built climate file sample is shown in Table 7.14 (below).

Table 7.14: AccuRate climate file showing where coded information in each row is identified



The AccuRate climate file consists of 60 columns of data. The columns consist of coded information for climate data required for the simulation and flag values, indicating whether the climate data was measured or estimated. Table 7.15 summarises the contents of each of the 60 columns.

Table 7.15: Summary of AccuRate's climate file data contents

Columns 1 and 2 contain a two letter code for the site (eg HO for Hobart)
Columns 3 and 4 contain the last two digits of the year number eg 07 for 2007
Columns 5 and 6 contain the month number (zero-filled) eg 01 for January
Columns 7 and 8 contain the day number (zero-filled) eg 01 for first of the month
Columns 9 and 10 contain the hour number 0-23 (0=midnight, 1=1am etc)
Columns 11 to 14 contain the Dry Bulb (Air) temperature in tenths of degrees C
Columns 15 to 17 contain the Moisture Content in tenths of g per kg
Columns 18 to 21 contain the Atmospheric (Air) Pressure in tenths of kPa
Columns 22 to 24 contain the Wind Speed in tenths of metres per second
Columns 25 to 26 contain the Wind Direction 0-16 (0=CALM,1=NNE, …, 16=N)
Column 27 contains the Cloud Cover 0-8 (0= no cloud; 8= full cloud)
Column 28 contains the Flag for Dry Bulb Temp. (0=Actual, 1=Estimated) Column 29 contains the Flag for Moisture Content (0=Actual, 1=Estimated) Column 30 contains the Flag for Atmospheric Pressure (0=Actual, 1=Estimated) Column 31 contains the Flag for Wind Speed (0=Actual, 1=Estimated) Column 32 contains the Flag for Cloud Cover (0=Actual, 1=Estimated) Column 33 contains the Flag for Wind Direction (0=Actual, 1=Estimated)
Columns 34 to 37 contain Global Solar Radiation on a horizontal plane (Wh/m2)
Columns 38 to 40 contain Diffuse Solar Radiation on a horizontal plane (Wh/m2)
Columns 41 to 44 contain the Normal Direct Solar Radiation (Wh/m2)
Columns 45 to 46 contain Solar Altitude in degrees (0 to 90)
Columns 47 to 49 contain the Solar Azimuth in degrees (0 to 359, 0=N, 90=E, …)
Column 50 contains the Flag for Global Solar Radiation. (0=Actual, 1=Estimated)
Column 51 contains the Flag for Diffuse Solar Radiation (0=Actual, 1=Estimated) Column 52 contains the Flag for Normal Direct Solar Radiation (0=Actual, 1=Estimated.)
Columns 53 and 54 contain the first two digits of the year number, e.g. 20 for 2010
Columns 55 to 60 are blank

AccuRate's original in-built weather file contents and format provided the base information data for creating the project weather file for this project.

7.5.2. Bureau of Meteorology (BOM) Climate File

A complete set of BOM climate data from Hobart's Ellerslie Road and the Hobart Airport station was obtained in 2008. Data obtained included: satellite derived daily global solar radiation values and half hourly values for the remaining climate data. BOM climate data was selected for the entire year 2007 and individual climate data was matched to AccuRate's required climate input data. Original BOM climate data delivered in notepad format was converted into EXCEL table format. All BOM climate data was derived from the Ellerslie Road Station (Station Number

94029, Latitude 42.89 ºS, Longitude 147.35 ºE, Elevation 51m). Listed below are the BOM data that were collected for the year 2007. Note that all half hourly values in the BOM data were averaged into hourly values in the EXCEL data base.

- Air temperature (ºC);
- Relative humidity (%);
- Station level pressure Ellerslie Road Elevation 51m (hPa);
- Wind speed (m/s), data measured at 10m height;
- Wind direction (16 compass points, N to NNW) converted into 1-16 vectors. 360=N, 1=NNE to 15=NNW;
- Cloud cover (0-8, 0=no cloud cover, 8=full cloud cover);
- Global solar radiation (MJ/m²). Daily measured radiation satellite values were converted into hourly radiation values. Daily values were divided by the sum of daily hourly sun altitudes angles and then multiplied by the sun altitude angle for each individual hour. MJ/m² values were converted into Wh/m².
- Diffuse solar radiation. No BOM data were available. Hourly diffuse solar radiation for Hobart was calculated from global solar radiation values. A sample EXCEL calculation formula was provided by the University of Adelaide to convert global solar radiation into diffuse radiation values (J Boland 2010, pers. comm. 25 March);
- Direct beam solar radiation. No BOM data were available. Hourly direct beam solar radiation was calculated from global solar and diffuse radiation data (Direct solar beam radiation = global radiation - diffuse radiation / sin of altitude).

7.5.3. Site Measured Climate File

The following site climate data were measured by the weather station located on the rooftop of the slab floor house:

- Air dry bulb temperature (ºC, to a tenth of a degree);
- Relative humidity (%);
- Wind speed (m/s);
- Wind direction (0º-359º);
- Global solar radiation (Wh/m²);
- North vertical solar radiation (Wh/m²)

Climate data were measured at 10 minute intervals from 5 July 2007 to 5 September 2007 and at intervals of 5 minutes from 6 September 2007 to 26 September 2007. The climate data were checked and cleaned using the same data cleaning process as the measured house data, and consisted of range and step checks and finally, the graphical checking of unexpected peaks and troughs. The data were averaged to one-hourly readings and stored.

A complete site climate data set was collected between 5 September 2007 and 26 September 2007. Table 7.16 presents a sample of the on-site climate file, as acquisitioned from the DT 80 data logger.

Table 7.16: Sample of the site climate data (EXCEL format)

DATA AVERAGING STARTS HERE. ALL SCALES AND WIND DIRECTION/SPEED DATA CONSIDERED CORRECT.							
		m/s	Deg. from Nth	Deg. Centgrd.	% RH	kw/sq_m	kw/sq_m
6/9/2007	1:00:00 PM	7.74563	205.18355	19.47771	35.49002	0.32661	0.44173
6/9/2007	1:05:00 PM	10.82517	351.76074	19.05207	39.24554	0.60724	0.85305
6/9/2007	1:10:00 PM	6.65398	192.37823	19.78958	35.07518	0.49924	0.69213
6/9/2007	1:15:00 PM	8.25591	177.0159	19.30822	38.11343	0.52521	0.7319
6/9/2007	1:20:00 PM	7.272	184.9097	19.48072	36.12559	0.61459	0.8519
6/9/2007	1:25:00 PM	7.89808	184.30019	19.47902	37.94512	0.18584	0.24244
6/9/2007	1:30:00 PM	10.25002	169.91263	17.91193	40.91792	0.25954	0.35377
6/9/2007	1:35:00 PM	10.77329	172.97968	17.12326	42.03335	0.61079	0.85332
6/9/2007	1:40:00 PM	9.19717	172.05998	17.50165	41.58142	0.59754	0.82651
6/9/2007	1:45:00 PM	8.15682	208.27592	18.96708	39.03234	0.61018	0.84664
6/9/2007	1:50:00 PM	7.29314	181.35695	19.18412	38.21769	0.52228	0.67188
6/9/2007	1:55:00 PM	9.71505	192.82501	18.59184	39.234	0.58799	0.80925
6/9/2007	2:00:00 PM	8.08082	210.63979	18.41893	40.68654	0.24062	0.33318
6/9/2007	2:05:00 PM	6.69032	174.07941	18.47278	38.96243	0.58834	0.82003
6/9/2007	2:10:00 PM	8.81508	213.80502	18.77082	39.27591	0.17585	0.23377
6/9/2007	2:15:00 PM	9.2485	194.3858	17.77205	40.12176	0.17117	0.21663
6/9/2007	2:20:00 PM	8.69248	188.50137	17.35881	41.66214	0.16403	0.21803
6/9/2007	2:25:00 PM	9.80251	210.70758	17.14646	41.80394	0.27176	0.37295
6/9/2007	2:30:00 PM	4.57043	188.0186	18.29817	38.90648	0.45522	0.64341
6/9/2007	2:35:00 PM	8.44203	172.75661	19.01917	35.70838	0.51618	0.72826
6/9/2007	2:40:00 PM	7.84162	184.799	19.31995	35.87874	0.51236	0.719
6/9/2007	2:45:00 PM	7.62718	195.5818	19.29534	35.95545	0.14781	0.18214
6/9/2007	2:50:00 PM	7.88956	196.34543	18.97644	36.55281	0.19705	0.19448
6/9/2007	2:55:00 PM	8.92915	177.6087	18.23884	38.85389	0.35333	0.43114
6/9/2007	3:00:00 PM	8.70583	182.04565	18.29216	38.90921	0.1915	0.20546
6/9/2007	3:05:00 PM	7.94345	216.47163	17.94094	40.62796	0.15044	0.18419
6/9/2007	3:10:00 PM	7.31784	180.93343	17.37962	40.67196	0.12184	0.13835
6/9/2007	3:15:00 PM	8.35964	171.29547	17.01033	41.46204	0.1878	0.1826
6/9/2007	3:20:00 PM	5.95531	203.15088	17.65876	40.56527	0.41119	0.59373
6/9/2007	3:25:00 PM	7.27461	214.3853	18.95891	35.42469	0.38081	0.58028
6/9/2007	3:30:00 PM	6.53987	188.1098	19.32708	35.21991	0.35229	0.53971
6/9/2007	3:35:00 PM	9.16114	181.77184	18.99177	35.98377	0.32374	0.50907
6/9/2007	3:40:00 PM	9.47221	185.84995	18.50467	36.72723	0.08619	0.13609
6/9/2007	3:45:00 PM	9.28747	181.63722	17.77922	40.11942	0.26718	0.4525
6/9/2007	3:50:00 PM	6.46302	188.21162	18.2823	38.33221	0.25239	0.43162
6/9/2007	3:55:00 PM	5.97225	179.91885	18.61995	38.11814	0.23407	0.40178
6/9/2007	4:00:00 PM	8.31524	192.53706	18.20979	38.72943	0.17181	0.29342
6/9/2007	4:05:00 PM	6.47459	191.81758	18.03333	38.00594	0.18467	0.32193
6/9/2007	4:10:00 PM	5.47827	217.30095	18.42722	37.75086	0.1914	0.33926
6/9/2007	4:15:00 PM	6.15444	170.96458	18.46345	38.17933	0.18652	0.33698

It should be noted, that only the period containing the completed set of site-measured weather data was used for the purpose of empirical validation of AccuRate.

7.5.4. Project Climate File

The project climate file consisted of a combination of BOM data and site measured data for the entire year 2007. For the free-running operation of the houses between 5 September and 26

September 2007, the measured site climate data were used, while for the remaining year the 2007 BOM weather data from the Ellerslie Road station were applied to the site-project climate file. Table 7.17 summarises the data acquisition of the site-project climate file for the empirical validation of AccuRate.

Table 7.17: Summary of the site-project climate data file

Col. No.	Description	Method
5-6	Month Number	On site data acquisition
7-8	Day Number	On site data acquisition
9-10	Hour Number	On site data acquisition
11-14	Dry Bulb Temperature to 0.1 degrees Celsius	On site data acquisition 29.6.2007-3.8 2007, 15.8 2007-26.9.2007, otherwise Ellerslie Road BOM data 2007 used.
15-17	Moisture Content	On site data acquisition 29.6. 2007-3.8.2007, 15.8.2007-29.6.2007, otherwise Ellerslie Road BOM data 2007 used
18-21	Atmospheric (air) Pressure	BOM – Ellerslie Road, Hobart. The data file includes a value for mean sea level air pressure. The sea height of the BOM Ellerslie Road and the Kingston site are both 51m above sea level. Therefore BOM file data used.
22-24	Wind Speed	On-site data acquisition 6.9.2007-26.9.2007, otherwise Ellerslie Road BOM data 2007 used.
25-26	Wind direction	On-site data acquisition 6.9.2007-26.9.2007, otherwise Ellerslie BOM data 2007 used.
27	Cloud cover	Not measured. Calculated data used from measured global solar radiation data between 29.8.2007-26.9.2007, otherwise Ellerslie BOM data 2007 used. (Calculated data with the program Make ACDB v9) Source: Lee and Stokes.
34-37	Global Solar Radiation	On-site data acquisition 1.9.2007-26.9.2007, otherwise BOM Ellerslie Road radiation values used. Converted from daily satellite values into hourly values.
38-40	Diffuse Solar Radiation	Not measured but calculated. Boland & Ridley supplied an Excel calculation model to convert measured global solar radiation to diffuse radiation values. This model was then used to calculate the diffuse radiation for this project.
41-44	Normal Direct Solar Radiation	Not measured but calculated from the values of global solar radiation and diffuses solar radiation.(global-diffuse/sin altitude)
45-46	Solar Altitude	Data adopted from existing Hobart Climate file
47-49	Solar Azimuth	Data adopted from existing Hobart Climate file

When the values for diffuse solar radiation and normal direct solar radiation were calculated, some values, for example, at times when the sun had a low altitude, were incorrect and were amended manually (J. Bowland 2010, pers. comm., 25 March). This problem in mathematically deriving diffuse radiation has been documented by previous researchers (Spencer 1982).

All the BOM data were taken from Hobart's Ellerslie Road station, some 8.6 km north of Kingston. While only a short distance from Kingston, the BOM weather data differed slightly, due to the micro-climate effect of Mount Wellington (1268m), which is situated near Ellerslie Road, Hobart. While the BOM weather data were more accurate then AccuRate's in-built climate data, they were not used for empirical validation comparison. Figure 7.17 shows the temperature range at the Kingston site and the BOM station at Ellerslie Road between 5 July 2007 and 26 September 2007. It can be seen clearly that temperature profiles differed up to 3.5ºC at maximum temperatures and up to 2.5ºC at minimum temperatures.

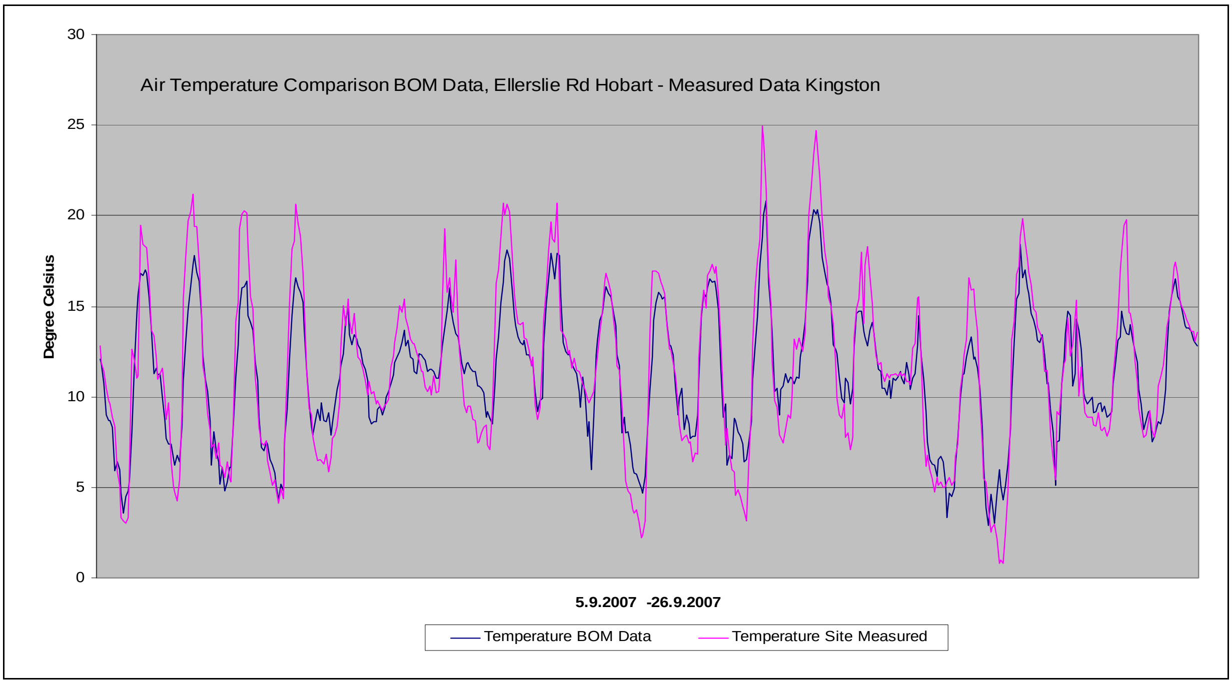


Figure 7.17: Temperature profile comparison between site-measured air temperature and the BOM data, measured at the Ellerslie Road station, Hobart

The project weather file was initially created in EXCEL format and finally transferred into an AccuRate txt climate file format.

7.6. AccuRate's Output Data

After completing the simulation process, the general output data were accessed from the AccuRate project manager screen's control button generating the following data:

- Summary of the star rating report;

- Building data report;
- Compare runs, providing graphical temperature profiles and temperature histograms.

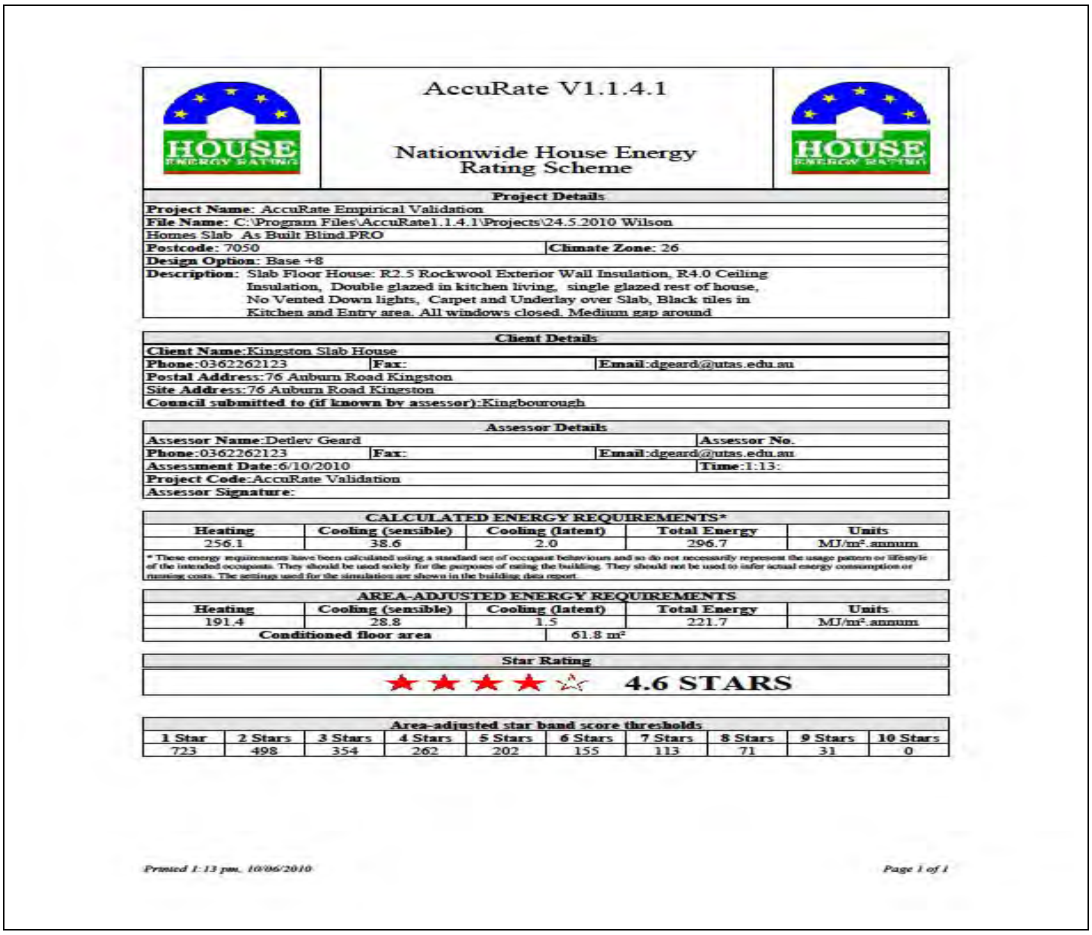
Specific output data can be obtained through the AccuRate's internal program file output data after each simulation and they include:

- Hourly temperature profiles for each zone, including external temperatures;
- Energy text, detailing the energy requirements to maintain a particular temperature range within conditioned zones;
- Output data, providing the mean temperature and the mean temperature range for each zone for each month of the year.

7.6.1. General Output Data

a) The Star Rating Report

The star rating report is the most general form of output and includes a star rating based on a heating and cooling load assessment. It represents the predicted energy use per square metre of floor area to heat and cool a house to maintain comfortable conditions in the designated conditioned zones. This report is mostly used by the home energy assessors to obtain building approval in compliance with part 3.12, Energy Efficiency in the BCA. Figure 7.18 shows the star rating summary for one of the slab floor house simulations.



AccuRate V1.1.4.1

Nationwide House Energy Rating Scheme

Project Details	
Project Name: AccuRate Empirical Validation	
File Name: C:\Program Files\AccuRate1.1.4.1\Projects\24.5.2010 Wilson Homes Slab As Built Blind.PRO	
Postcode: 7050	**Climate Zone**: 26
Design Option: Base +8	
Description: Slab Floor House: R2.5 Rockwool Exterior Wall Insulation, R4.0 Ceiling Insulation, Double glazed in kitchen living, single glazed rest of house, No Vented Down lights, Carpet and Underlay over Slab, Black tiles in Kitchen and Entry area. All windows closed. Medium gap around	

Client Details		
Client Name:Kingston Slab House		
Phone:0362262123	**Fax**:	**Email**:dgeard@utas.edu.au
Postal Address:76 Auburn Road Kingston		
Site Address:76 Auburn Road Kingston		
Council submitted to (if known by assessor):Kingbourough		

Assessor Details		
Assessor Name:Detlev Geard		**Assessor No.**
Phone:0362262123	**Fax**:	**Email**:dgeard@utas.edu.au
Assessment Date:6/10/2010		**Time**:1:13:
Project Code:AccuRate Validation		
Assessor Signature:		

CALCULATED ENERGY REQUIREMENTS*				
Heating	**Cooling (sensible)**	**Cooling (latent)**	**Total Energy**	**Units**
256.1	38.6	2.0	296.7	MJ/m².annum

* These energy requirements have been calculated using a standard set of occupant behaviours and so do not necessarily represent the usage pattern or lifestyle of the intended occupants. They should be used solely for the purposes of rating the building. They should not be used to infer actual energy consumption or running costs. The settings used for the simulation are shown in the building data report.

AREA-ADJUSTED ENERGY REQUIREMENTS				
Heating	**Cooling (sensible)**	**Cooling (latent)**	**Total Energy**	**Units**
191.4	28.8	1.5	221.7	MJ/m².annum
Conditioned floor area		61.8 m²		

Star Rating

★★★★☆ **4.6 STARS**

Area-adjusted star band score thresholds									
1 Star	**2 Stars**	**3 Stars**	**4 Stars**	**5 Stars**	**6 Stars**	**7 Stars**	**8 Stars**	**9 Stars**	**10 Stars**
723	498	354	262	202	155	113	71	31	0

Printed 1:13 pm, 10/06/2010 *Page 1 of 1*

Figure 7.18: Summary of the star rating report for the slab floor house

b) Building Data Report

This report can also be accessed through the project manager screen and provided a detailed report of the construction input parameters. It is useful for checking the project's input data details at the completion of a simulation. The building data report summarises construction details, including specified areas and thickness of pre-selected building materials.

c) Compare Run Report

The Compare Run control button allows access to predicted temperature profiles for each designated zone for any time period of the year. This tool allows the user access to check predicted temperature gradient in the building, and as a design tool it provides the building designer with options for thermal design improvements to the building. Figure 7.19 depicts a sample of the predicted temperature range for the kitchen/dining/living area, bedroom 1 and the external temperature in the slab floor house during a cold period of the winter.

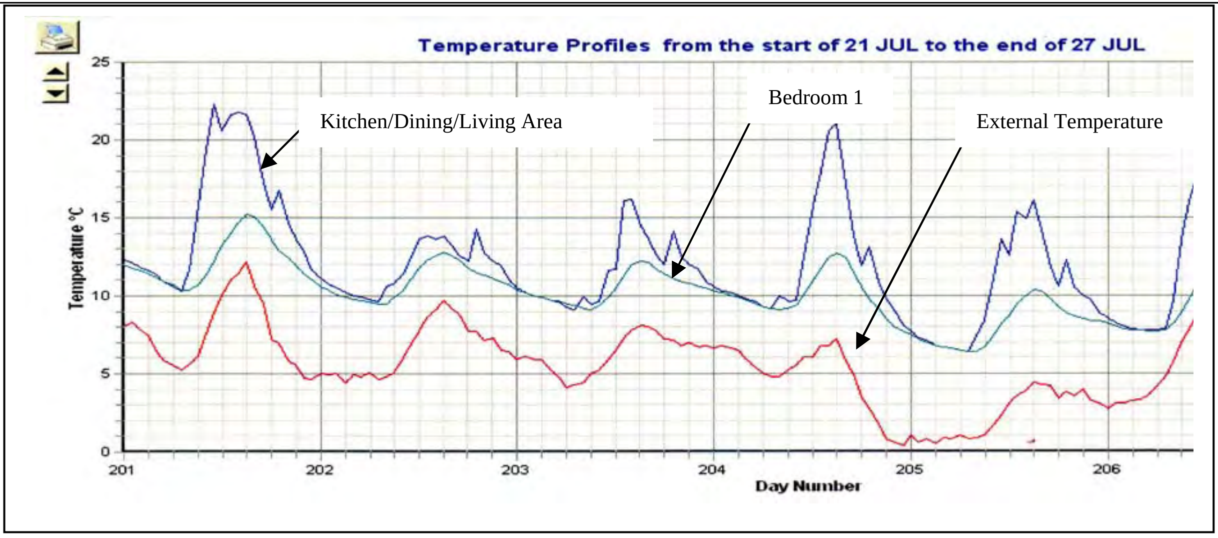


Figure 7.19: AccuRate's general output data, predicted temperature profile for a typical cold winter period in the slab house's kitchen/dining/living area, bedroom 1 and external temperature

7.6.2. Specific Output Data

a) Temperature File

The AccuRate temperature file provides the simulated hourly temperature for each zone, including the non-conditioned zones inside the house and the roof and subfloor space. The outdoor temperature is also included in the temperature file. Table 7.18 shows a sample of the temperature file for one of the simulations of the houses.

Table 7.18: Sample of AccuRate's temperature files of hourly predicted temperatures

Month	Day	Hour	Outdoor	Kitchen Dining Livin	Bed 1	Bed 2	Bed 3	EnSuite	Laundry	Bath	Roofspace
1	1	0	17	20.9	21.1	20.3	20.6	21.3	19.9	16.5	17
1	1	1	16.4	20.7	21	20.1	20.4	21.2	19.8	16.3	16.7
1	1	2	15.8	20.4	20.8	19.9	20.2	21	19.5	15.5	16.2
1	1	3	14.9	20.1	20.5	19.6	19.8	20.8	19.2	15	15.6
1	1	4	14.3	19.8	20.2	19.3	19.5	20.5	18.8	14.5	15
1	1	5	14.6	19.8	20.1	19.1	19.4	20.4	18.8	14.9	14.6
1	1	6	15.1	20.3	20.2	19.4	20.4	20.6	19.3	16.2	14.8
1	1	7	16.3	20.7	20.4	19.8	21.3	20.5	19.5	20.9	16
1	1	8	18	21.9	20.6	20.5	21.8	20.7	20.3	26.6	18.5
1	1	9	19.7	22.9	21.2	21.9	21.6	21	21.8	33.1	22.1
1	1	10	21.4	23.1	22.4	23.3	23.5	21.6	22.3	36.8	25.9
1	1	11	22.2	23.8	23.3	24.4	24.2	22.2	23.1	37.2	28.7
1	1	12	23.8	24.8	24.3	25.6	25.4	22.8	24.3	35.4	30.2
1	1	13	24.1	25.3	24.9	26.1	25.8	23.7	24.7	40.5	31.6
1	1	14	24.5	23	25.6	26.5	26	24.2	25.1	39.9	33.3
1	1	15	23	24.7	25.5	25.6	24.9	23.5	24.1	37.6	33.4
1	1	16	21.8	23.8	24.9	24.6	23.8	22.7	23.1	32	32.2
1	1	17	20.4	22.8	23.9	23.2	22.5	21.9	21.9	26.9	29.8
1	1	18	19.2	21.9	22.6	21.8	21.3	21.1	20.8	22.2	27

AccuRate's output temperature files were compared with the measured temperature of the houses for the empirical validation of AccuRate.

b) Energy text

AccuRate uses the thermal simulation temperature data to establish the quantity of energy required to maintain a comfortable temperature range within the building. The annual sum of these values is used to calculate the energy required to heat or cool the building. The total energy requirement is then converted into a star rating. For the empirical validation the houses were simulated in free-running operation, with no heating or cooling during that period. As a result, all the values in the energy text had a zero value.

c) Output File

AccuRate's output file summarises the monthly mean temperature and mean temperature ranges for all zones of the house for each month. This output file data provides the AccuRate user with a quick comparisons of predicted mean temperatures experienced in the building.

7.7. The Effects of Modified Construction Inputs and Site-Measured Climate File on AccuRate Simulation

Extensive modifications of AccuRate's input data were made for more accurate representation of the houses for the empirical validation process. These included two major input modifications, namely: the construction and the climate input data. As a result of calculating the timber framing ratio, the value of the wall insulation was reduced by 36% and the ceiling insulation by 23%. The effect of the as-built modifications to AccuRate's input file can be observed in Figure 7.20. Modifications were based on the calculation of actual framing ratios for wall and ceiling insulation, the actual window framing ratios and measured infiltration rates.

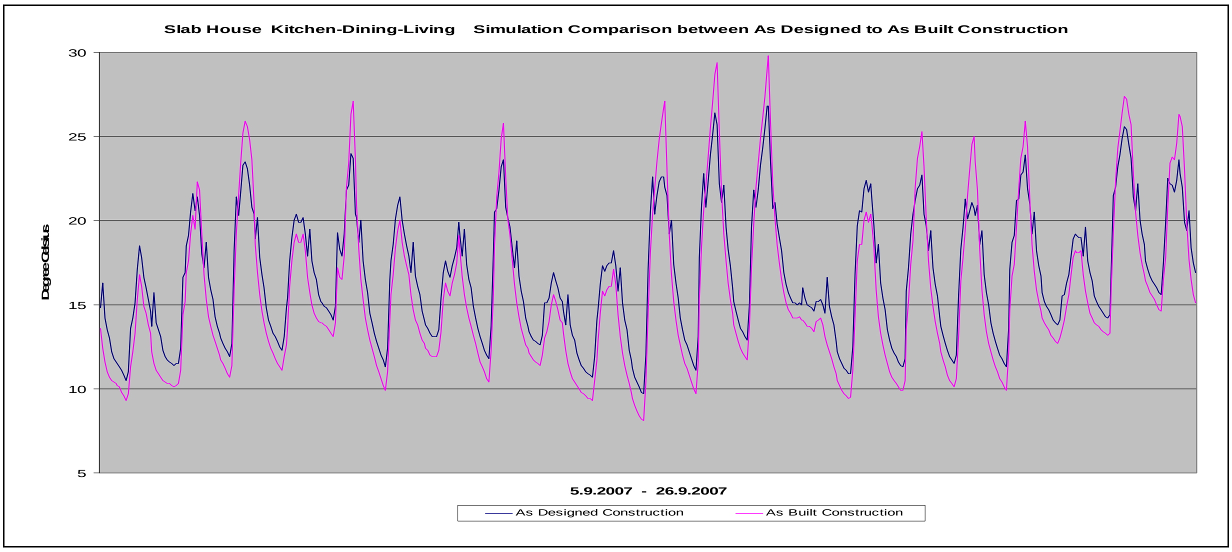


Figure 7.20: AccuRate simulation comparison between as-designed and as-built condition of the slab house

Figure 7.20 shows a noteworthy difference in thermal performance in the kitchen/dining/living area of the slab floor house, with the as-built construction showing up to 4.5ºC higher maximum temperature and up to 1.4ºC lower minimum temperature compared to AccuRate's standard simulation. This difference is due to the decreased wall and ceiling insulation values, calculated when framing wall and ceiling timber ratios and insulation gaps around the recessed ceiling light fittings were included in the as-built simulation procedures. There was a significant difference between the site-measured climate data and AccuRate's TMY climate file. Figure 7.21 shows the difference of AccuRate's inbuilt temperatures for Hobart (Climate Zone 26) and site-measured temperatures between 5 September and 26 September 2007.

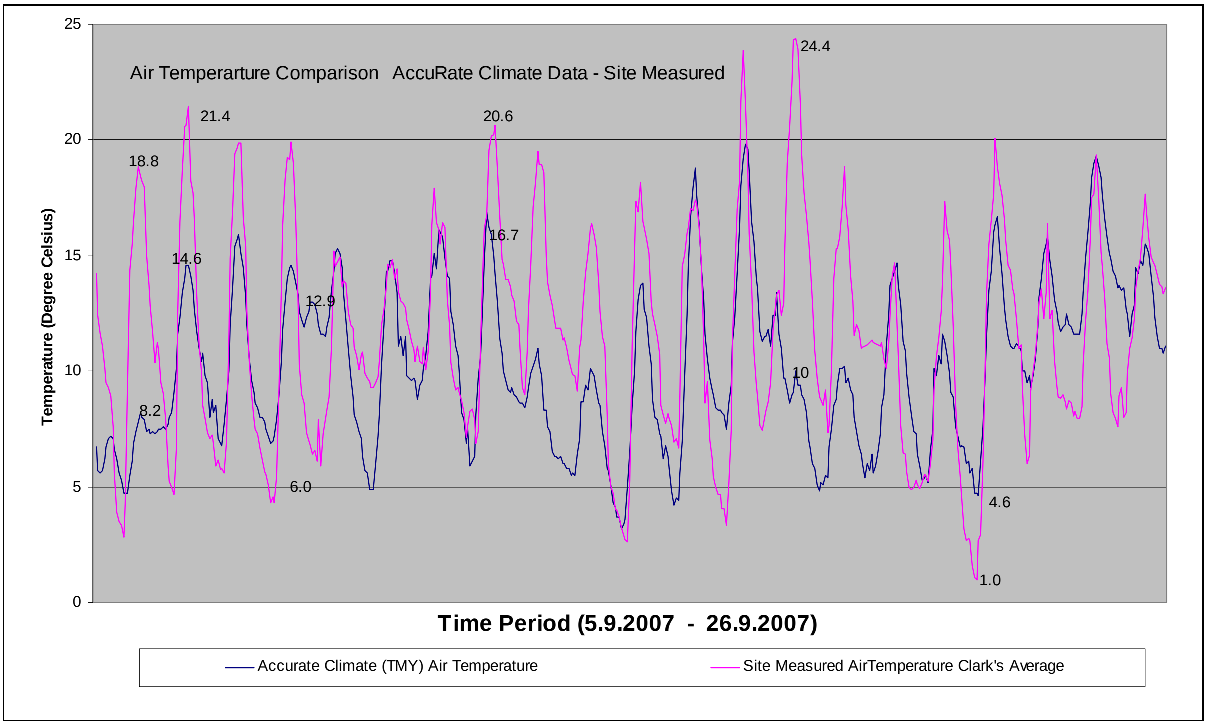


Figure 7.21: Temperature comparison between AccuRate in-built climate data (TMY) and site measured climate data

Maximum site measured temperatures were up to 14.4ºC higher and minimum air temperature up to 4ºC lower compared to AccuRate's inbuilt air temperature data. These significant differences of external temperatures can significantly affect the simulated thermal performance of buildings. Figure 7.22 presents the comparison of global solar radiation between AccuRate's climate data and site measured solar radiation data. There is a significant difference between AccuRate's global solar radiation data and the site-measured values.

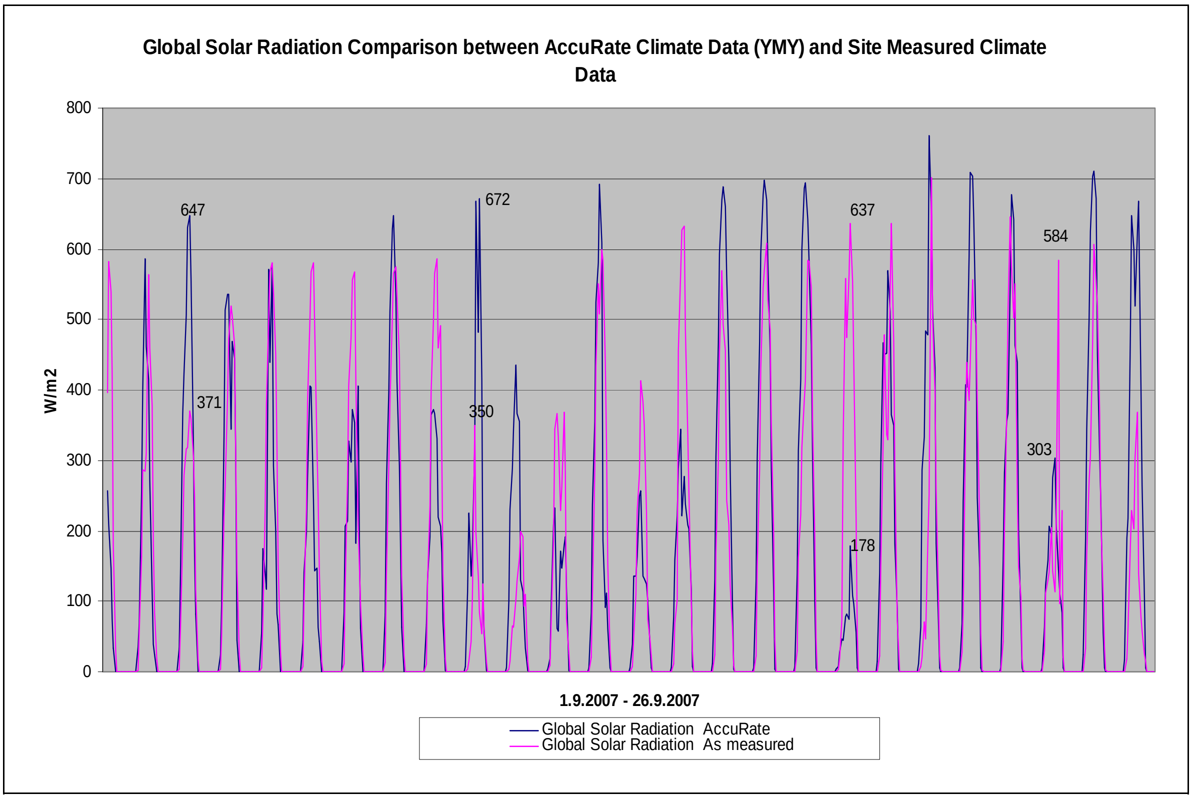


Figure 7.22: Global solar radiation data comparison between AccuRate climate data (TMY) and site-measured climate data

Differences up to 459 W/m² between site-measured and AccuRate in-built data were recorded between 1 September 2007 and 26 September 2007.

Figure 7.23 shows AccuRate's predicted thermal temperature profile comparison for the living room of the slab floor house, using the in-built AccuRate climate data and the site-measured climate data. The comparison of temperature profiles shows a significant temperature difference between AccuRate's simulation, using original inbuilt TMY climate data, and AccuRate's simulation, using site-measured climate data.

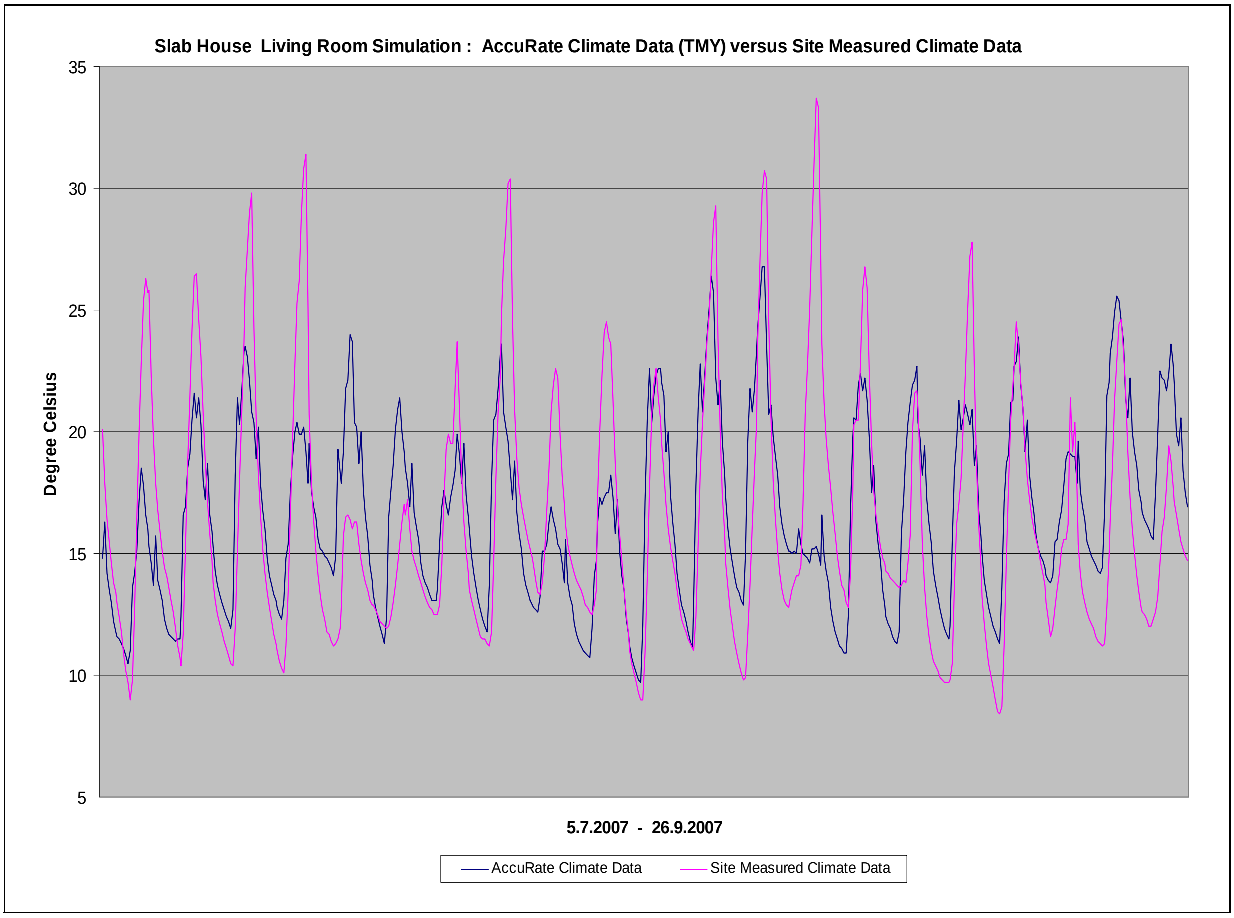


Figure 7.23: AccuRate simulation based on AccuRate's TMY climate and site-measured climate data

Temperature predictions in the living room of the slab floor houses using site-measured climate data were up to 17ºC higher and up to 3º lower compared to simulation predictions based on AccuRate's in-built climate data.

7.8. Summary

This chapter demonstrates clearly the importance of using measured input data, that is, the construction details of the as-built house and the site-measured climate data. While there was a relatively smaller difference using as-built construction compared to the as-designed construction, there was a significant difference in the simulated thermal performance using AccuRate's in-built TMY climate data compared to site-measured climate data. For the purpose of empirical validation, the use of as-built construction and site-measured climate data has been demonstrated to be necessary.

The graphical comparison between simulated and measured temperatures and the statistical empirical validation analysis will be addressed in Chapter 8.

Chapter 8: Empirical Validation of AccuRate: Results & Discussion

8.1. Introduction

Chapter 7 described the preparation of AccuRate's input data for the empirical validation process and demonstrated clearly the importance of using measured input data, that is: the construction details of the as-built house and site measured climate data.

This chapter focuses on the empirical validation of AccuRate and is presented in three parts. Part 1 discusses the approaches of using air or globe temperatures for validating AccuRate's simulated temperatures. Part 2 presents the graphical comparison of the simulated and measured temperatures in selected zones of the houses, as a means of examining temperature trends. Part 3 looks at the statistical analysis of the simulated and measured temperatures of the houses, examining the residuals and various correlations between the zones of the houses and the parameters of external climate.

8.2. Selecting the Appropriate Temperature Measurements for Validation

8.2.1. Comparison of Globe and Air Temperatures

This section assesses whether air or globe temperatures should be used for validating AccuRate's simulated temperatures. Measurements were taken at different heights to gain a wider understanding of air stratification in the rooms. In addition, there is little information available on the relationship between air and mean radiant temperatures in brick veneer houses, especially in free-running operation. Therefore, the comparison of air temperature with globe temperature was an essential part of this research. The comparison of various temperatures is presented for the slab floor house only, since temperature comparisons for the 4 and 5-star timber houses showed similar trends. The temperature sensors installed in the houses were as follows:

- Air temperature sensors installed at the centre of rooms at three height levels (0.6m, 1.2m and 1.8m from floor level);
- Air temperature sensors on the walls, installed at a height of 1.2m from floor level;
- Globe temperature sensors, installed at the centre of the rooms at a height level of 1.2m from floor level.

Figures 8.1 to 8.4 and Tables 8.1 to 8.2 show comparisons of the air temperatures and globe temperatures in the living room and bedroom 1 of the slab floor house from 5 September to 26 September 2007. Air and globe temperature sensors were installed at the centre of the room at a height of 1.2m from floor level. The living room, located at the north-east side of the house, was exposed to a considerable amount of solar radiation through large windows and sliding glass doors. Bedroom 1, located at the south-west side of the house experienced only a very small amount of solar radiation during early mornings. Figure 8.1 shows the comparison of air and globe temperatures at the living room in the slab floor house.

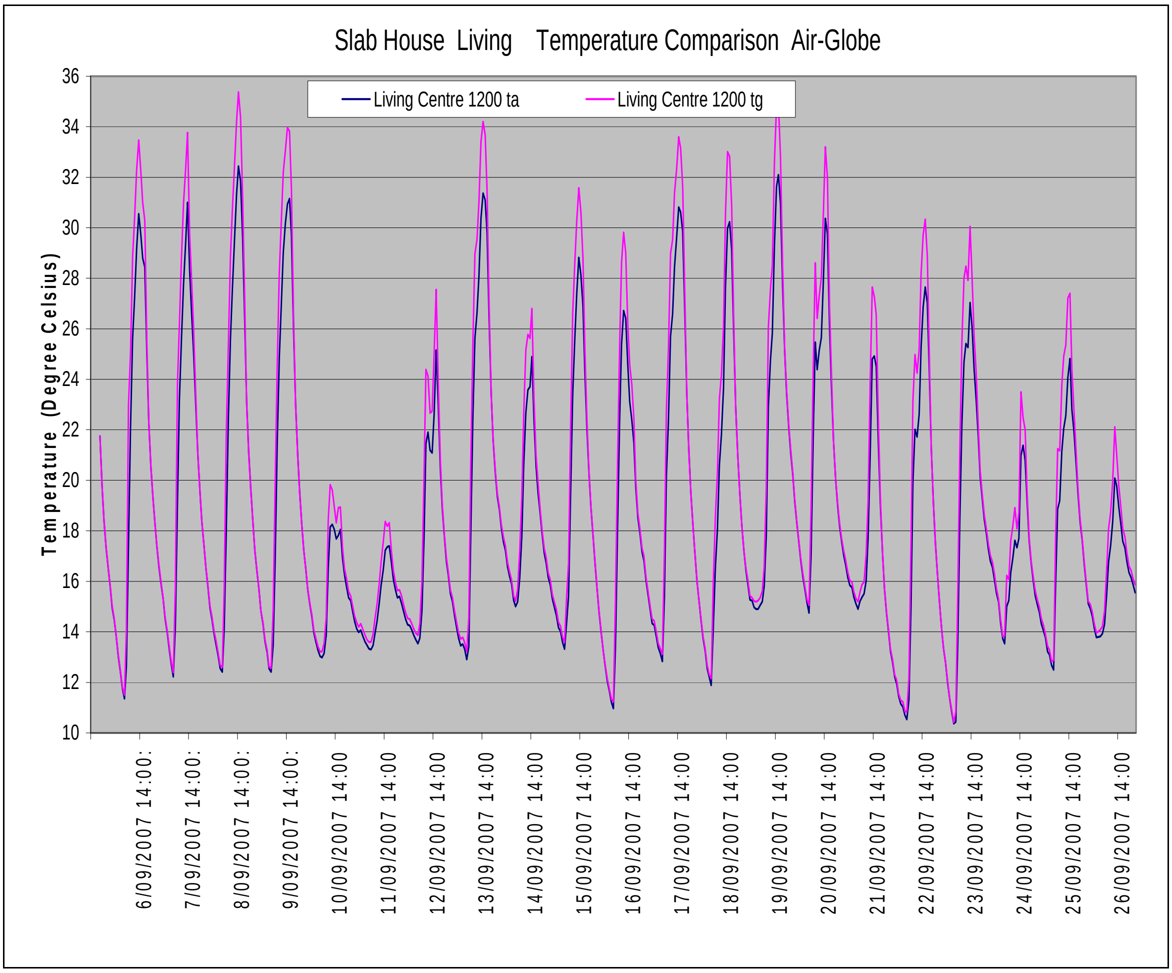


Figure 8.1: Comparison of air and globe temperature in the living room of the slab floor house

While the minimum globe temperatures in the living room are very similar to the air temperatures, (globe temperature up to 0.3ºC higher), the maximum globe temperatures are on average about 3ºC higher. The higher globe temperatures are due to the effect of direct solar radiation warming the surfaces of the room. Table 8.1 presents a summary of the comparison between the globe and air temperature for the living room of the slab floor house.

Table 8.1: Comparison of air and globe temperatures in the living room of the slab floor house

Description	Globe temperature (ºC)	Air temperature (ºC)	Differences (Globe temperature ºC– Air temperature ºC)
Temperature range	10.4-35.3	10.4-32.4	
Average temperature	19.7	18.7	+1.0
Average minimum temperature	13.1	12.9	+0.2
Average maximum temperature	29.8	27.2	+2.6

Figure 8.2 shows the comparison of daily maximum and minimum globe and air temperatures in the living room of the slab floor house and it confirms that the differences of the maximum temperatures are larger than the differences of the minimum temperatures.

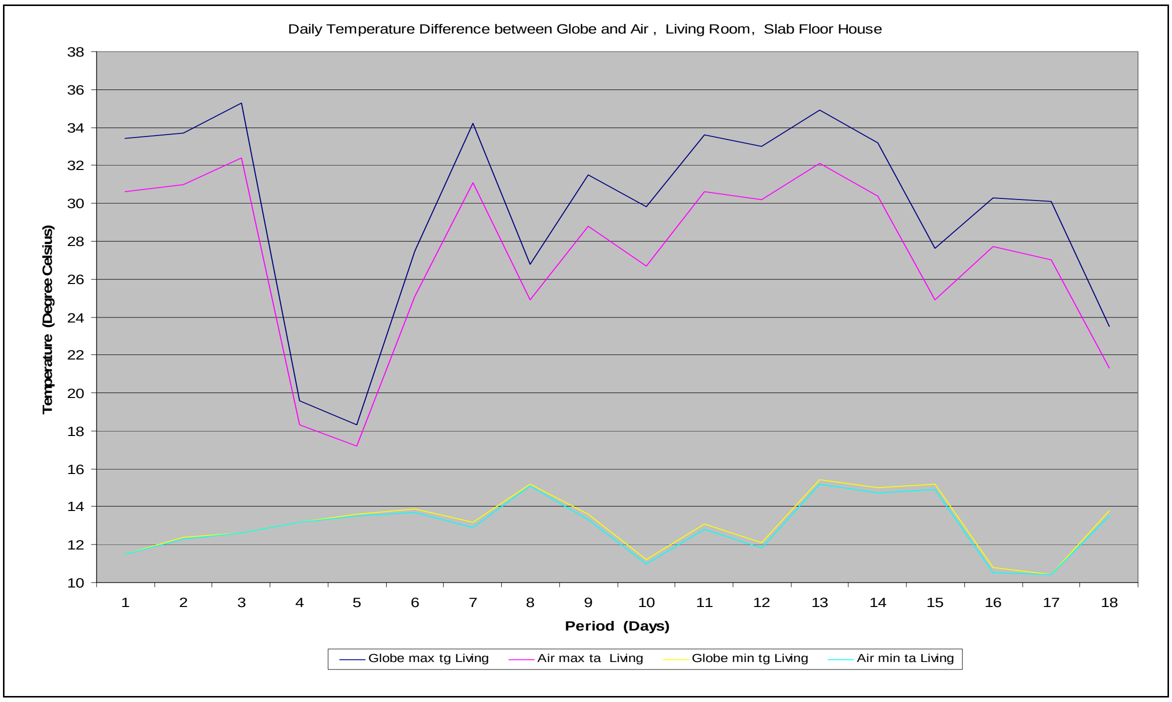


Figure 8.2: Comparison of daily maximum and minimum temperatures of globe and air temperature in the living room of the slab floor house

Figure 8.3 shows the comparison of air and globe temperatures in bedroom 1 of the slab floor house.

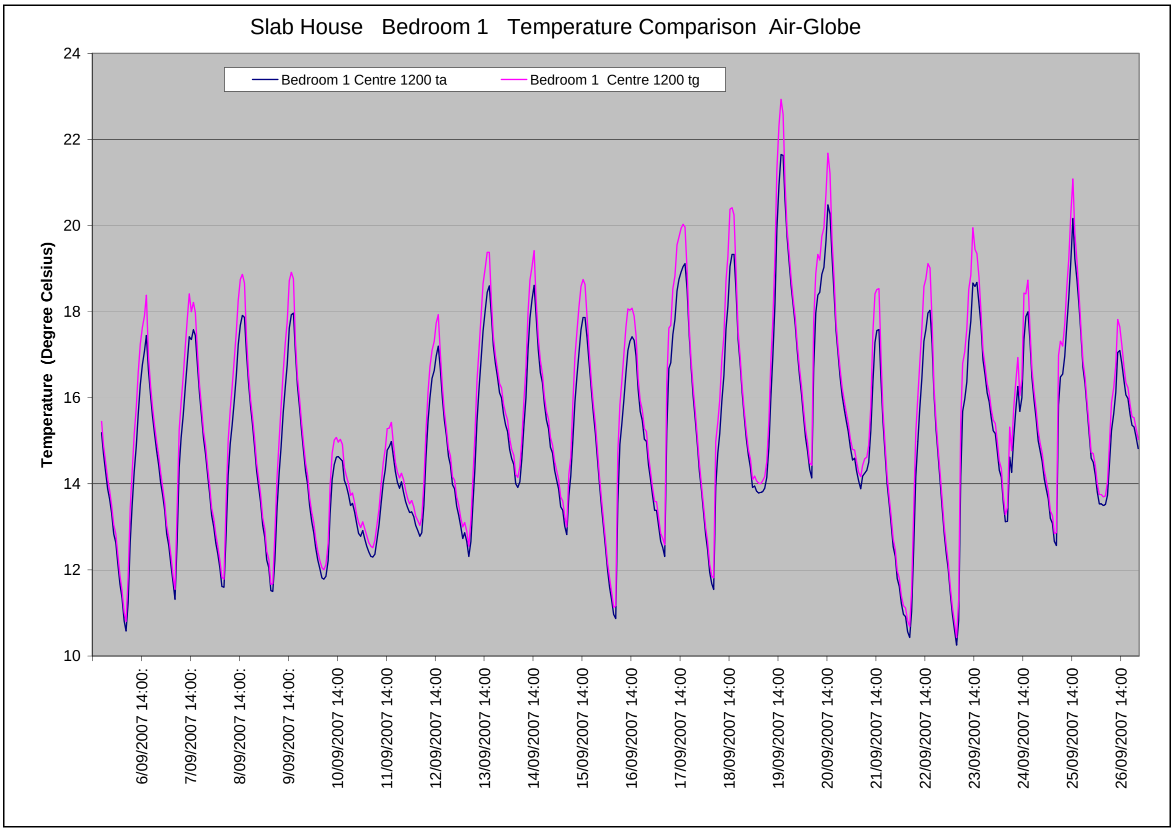


Figure 8.3: Comparison of air and globe temperatures in bedroom 1 of the slab floor house

A similar trend to the living area in globe and air temperatures is observed in bedroom 1, but with lesser differences in the maximum temperatures. As in the living room, minimum air temperatures are very close to the globe temperature (globe temperature up to 0.2ºC higher). The maximum globe temperatures in bedroom 1 are, on the average, about 1ºC higher than the air temperature. Table 8.2 shows the summary comparison between the globe and air temperature for bedroom 1 in the slab floor house.

Table 8.2: Comparison of air and globe temperatures in bedroom 1 of the slab floor house

Description	Globe temperature (ºC)	Air temperature (ºC)	Differences (Globe temperature ºC – Air temperature ºC)
Temperature range	10.4-22.9	10.2-21.6	
Average temperature	15.5	15.1	+0.4
Average minimum temperature	12.4	12.1	+0.3
Average maximum temperature	18.7	18.0	+0.7

Figure 8.4 shows the differences between daily maximum and minimum globe and air temperatures in bedroom 1 of the slab floor house. The table shows higher globe temperatures for the average temperature and for the average minimum and maximum temperature. Figure 8.4

shows the difference of maximum and minimum temperature of globe and air temperature in bedroom 1 of the slab floor house.

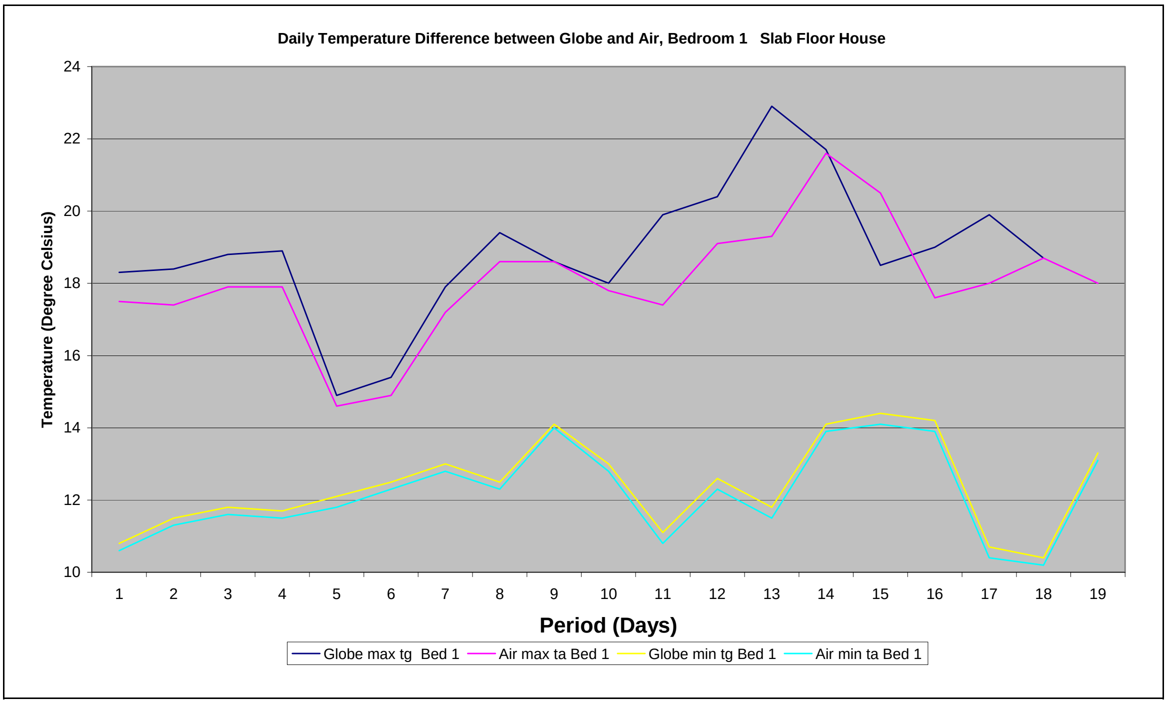


Figure 8.4: Comparison of daily maximum and minimum temperature of globe and air temperature in bedroom 1 of the slab floor house

There is a difference between the maximum globe and air temperature (globe temperature up to 2.5ºC higher), while the difference between the minimum globe and air temperature is much less significant. This is a similar trend to the differences between maximum and minimum temperatures in the living room of the slab floor house.

Based on the above results, we can conclude that as a result of daily solar radiation gains in the living room, maximum mean radiant temperatures are higher, compared to air temperatures. In a previous study by Delsante (2006), he compared air and globe temperatures in a mudbrick house in Melbourne and reported that measured globe and air temperatures were very similar (differences 0.1ºC or less) during the free-running period; however they differed by up to 2ºC during the heated periods. In this case, the globe temperature was lower. The difference of the globe temperature and the air temperature during the free-running period showed very similar figures for the mudbrick house in Melbourne, with most differences being 0.1ºC or less, with a maximum differences of 0.4ºC, while the difference of globe temperature and air temperature were up to 3ºC higher in the brick veneer houses in Kingston. The differences of globe temperature can be attributed to the significantly higher thermal mass of the walls and concrete floor in the mudbrick house, where the mudbrick walls and concrete flooring stayed cooler compared to the low mass plasterboard walls and timber flooring in the Kingston houses.

8.2.2. Comparison of Air Temperatures at Different Height Levels

As discussed previously, air temperature was also measured at the centre of the rooms at three height levels to observe stratification, if any, of air temperature in the rooms. Another reason for installing several temperatures sensors was to provide redundancy in case of a failure of one sensor, allowing the readings of nearby sensors to be used. Figure 8.5 shows the comparison of air temperature taken at three levels at the centre of the living room of the slab floor house.

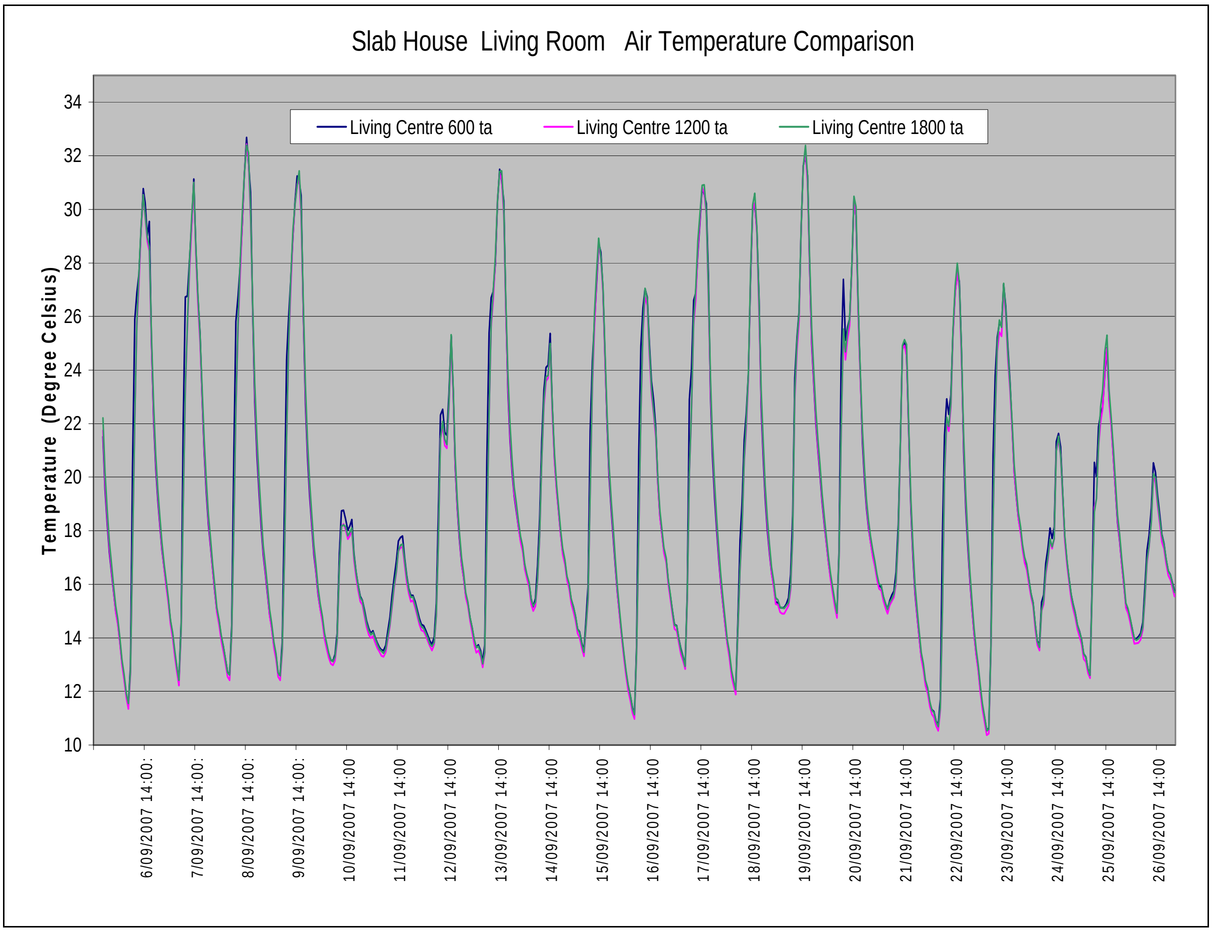


Figure 8.5: Comparison of air temperature at different height levels in the living room of the slab floor house

As can be seen in Figure 8.5 the temperatures measured at different height levels in the living room are very similar.

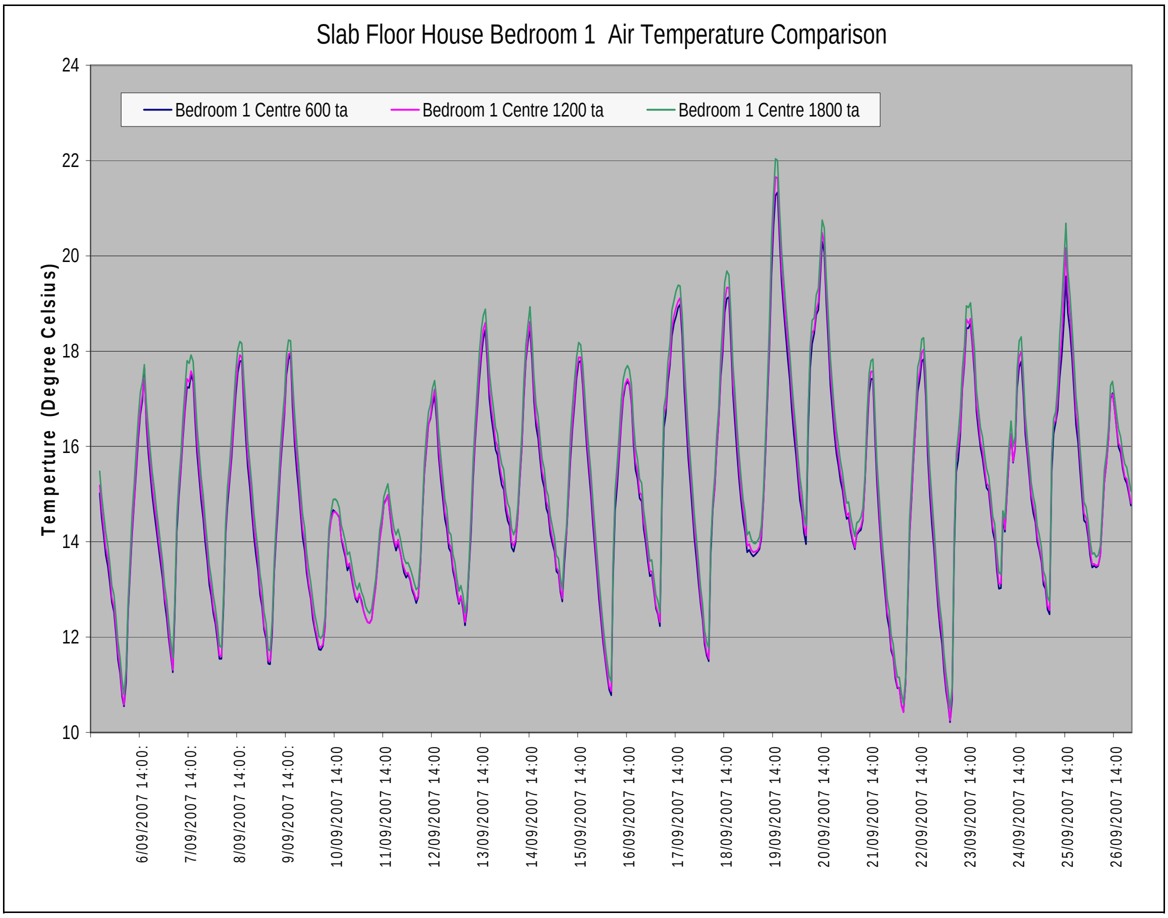


Figure 8.6: Comparison of air temperature at different height levels in bedroom 1 of the slab house

Figure 8.6 presents the comparison of air temperature at different levels taken at the centre of bedroom 1 of the slab floor house. In this case, the maximum temperatures measured at 1.8m are at the average about 0.3ºC higher when compared with the other temperatures. Otherwise, temperatures at the 0.6m level and 1.2m level are very similar. The higher maximum temperature measured at 1.8m level is likely to be the result of warmer air rising up to the ceiling level.

8.2.3. Comparisons of Air Temperatures at Different Locations

Air temperature was also measured by sensors located on the walls of the rooms at a height of 1.2m from floor level. The air temperature measured at the centre of the rooms and the air temperature measured at the walls were compared to investigate the temperature gradients in the rooms.

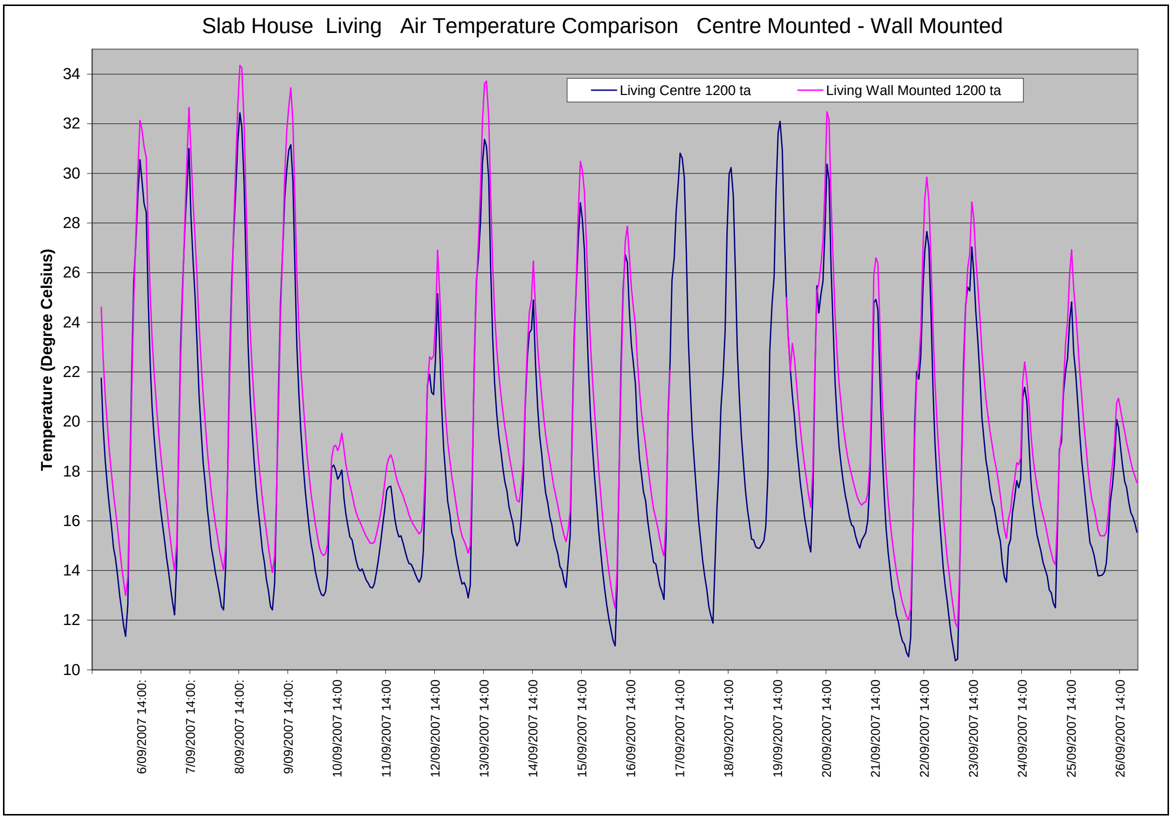


Figure 8.7: Comparison of air temperatures at the centre and on the wall in the living room of the slab floor house

Figure 8.7 shows the temperature comparison between the wall-mounted and centre-mounted sensor in the living room of the slab floor house. There is a noteworthy difference in the temperature readings with the wall-mounted sensor, showing continuously higher temperatures during the measured period. The summary of temperature comparisons for the living room can be observed in Table 8.3.

Table 8.3: Comparison of the centre and wall-mounted temperatures in the living room of the slab floor house

Description	Wall-Mounted Sensor (ºC)	Centre-Mounted Sensor (ºC)	Differences (Wall-Mounted to Centre-Mounted Sensors (ºC)
Temperature range	11.7 – 34.2	10.4-32.4	
Average temperature	20.1	18.7	+1.4
Average minimum temperature	14.3	12.6	+1.7
Average maximum temperature	28.0	26.9	+1.1

Figure 8.8 shows the daily temperature differences between the wall-and centre-mounted sensors in the living room of the slab floor house. Differences between the minimum temperatures of the wall-mounted and centre-mounted sensors are constant.

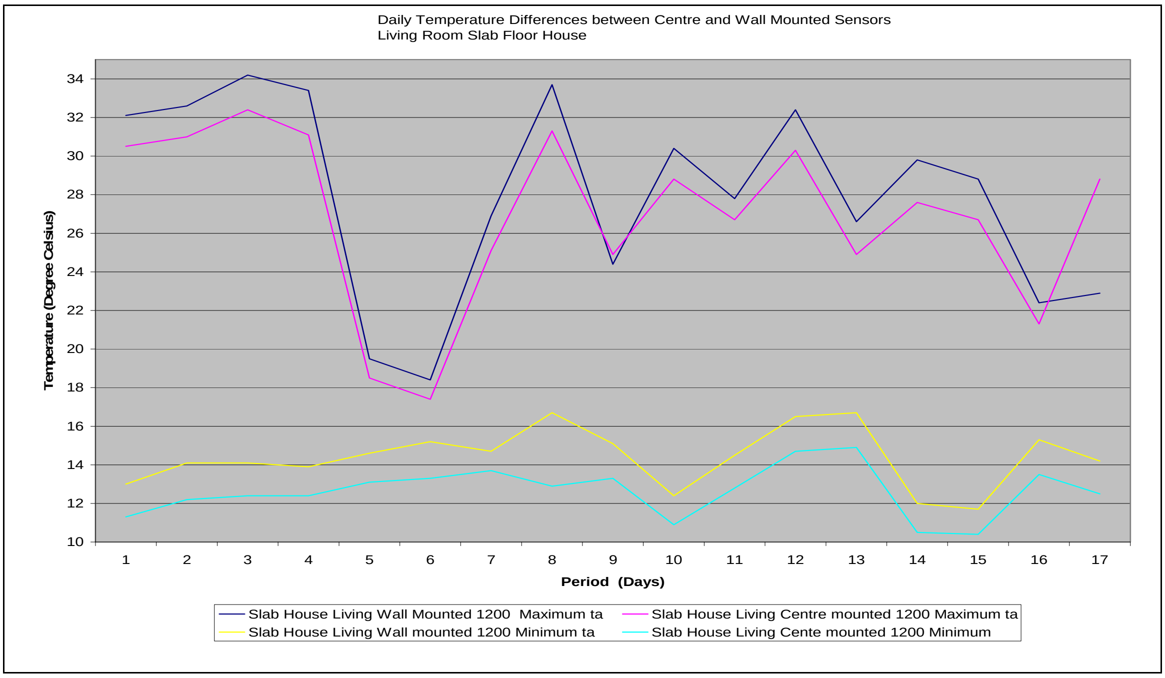


Figure 8.8: Daily temperature difference between wall and centre mounted sensors in the living room of the slab floor house

Figure 8.9 shows the temperature comparison between the wall-mounted and centre-mounted sensor in bedroom 1 of the slab house.

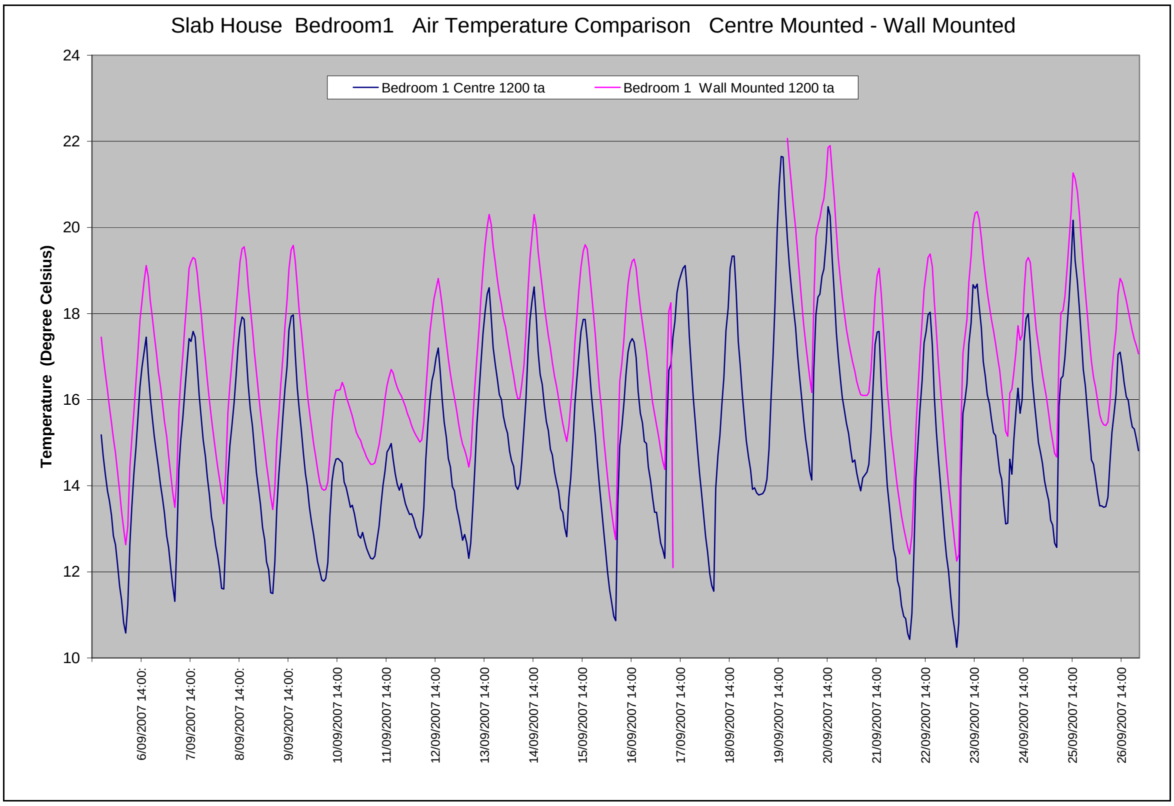


Figure 8.9: Temperature comparison of centre-mounted and wall-mounted sensors in bedroom 1 of the slab floor house

The wall-mounted sensor indicates about 2ºC higher minimum and maximum temperatures than the centre-mounted sensors throughout. The summary of temperature comparisons between the wall-mounted and centre-mounted sensors for bedroom 1 is shown in Table 8.4.

Table 8.4: Comparison of wall-mounted and room centre-mounted temperature sensor in bedroom 1 of the slab floor house

Description	Wall-Mounted Sensor (ºC)	Centre-Mounted Sensor (ºC)	Differences (Wall-Mounted – Centre-Mounted Sensors(ºC)
Temperature range	12.2-21.9	10.2-20.4	
Average temperature	16.9	15.1	+1.8
Average minimum temperature	14.4	12.0	+2.4
Average maximum temperature	19.3	17.5	+1.8

Table 8.4 shows higher temperatures for all temperatures for the wall-mounted sensors, with the average minimum temperature 2.4ºC and the average maximum temperature 1.8ºC higher than the room centre-mounted sensors. Figure 8.10 shows the daily temperature differences between the wall and centre-mounted sensors in bedroom 1 of the slab floor house.

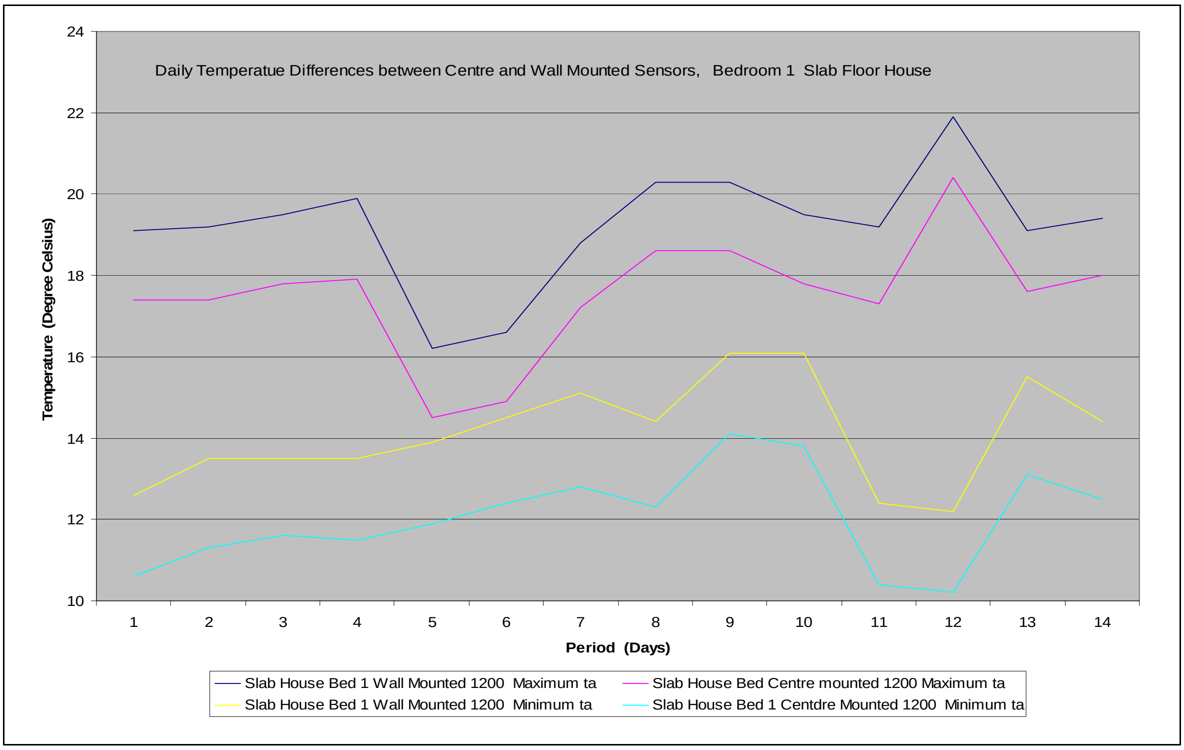


Figure 8.10: Daily temperature difference between wall and centre-mounted sensors in bedroom 1 of the slab floor house

In both the living room and bedroom 1 of the slab floor house, the wall-mounted sensors continuously recorded higher temperatures. The higher air temperatures recorded by the wall-mounted sensors showed that the wall-mounted air temperature sensors were affected by the higher surface temperature of the walls in both the living room and in the bedroom. As shown in Figures 8.1 and 8.4 the globe temperature showed up to 3ºC higher maximum temperature compared to the centre mounted air temperature sensors, indicating higher mean radiant temperatures at the walls. The higher mean radiant temperature at the walls is a result of solar radiation entering the room through north facing glazing firstly warming the walls before warming up the air temperature.

8.2.4. Selection of Appropriate Temperature to Validate AccuRate

The comparison of measured temperatures in the test houses indicates the following trends:

- Minimum globe and air temperatures are very similar;
- Maximum globe temperatures are higher than air temperature (average 2.6ºC in the living room and 0.7ºC in bedroom 1);
- Air temperatures measured at the centre of the living room at various height levels are very similar;
- Air temperatures measured at 1.8m height at the centre of bedroom 1 showed slightly higher values (average 0.3ºC) than at 0.6m and 1.2m;

- Wall-mounted sensors show a continuously higher reading than the centre-mounted sensors, in both the living room and bedroom 1. This is especially the case in bedroom 1, where the average minimum air temperature of the wall-mounted sensor is 1.8ºC higher and the average maximum air temperature is 2.2ºC higher, compared to the centre-mounted sensors.

Dewsbury (2011) reported that the measured globe temperatures in the test cells in Launceston were, on average, 0.8ºC to 1.0ºC higher, compared to air temperatures during a six day free-running operation between 29 July 2007 and 3 August 2007. Delsante (2006) stated that the globe temperature measurements in a mudbrick house in Melbourne were almost identical (<0.4ºC) during a four day free-running period. Benton et al. (1990) measured environmental conditions in 10 office buildings located in the San Francisco Bay region and reported that at 1.1m above floor level, the average differences in values between air temperature and globe temperature was only 0.10ºC for the entire season. Albright & Scott (1997) collected data at a barn located at the Cornell Teaching and Research Centre. They reported that the data showed that the mean radiant temperature in a closed room measured by the globe thermometer was never more than 0.5ºC higher than the air temperature, even at noon. Muncey (1979) reported that in an enclosed room with no ventilation and heat input into a room except through the bounding surfaces, the radiant temperature and the air temperature are equal. Chen confirmed by e-mail on 17 December 2011 that 'the multi-zone model used by the CHENAH engine assumes a uniform temperature for each room. The average air temperature thus is believed to be better representing the zone temperature in comparison to individual point temperature of air or globe temperature'. Based on the advice from the CSIRO's principle researcher the centre mounted average air temperatures, taken from 0.6m, 1.2m and 1.8m from floor level, were used for the comparison with AccuRate's simulated temperatures.

8.3. Analysis of Empirical Validation Graphs

In this section, the measured and simulated temperatures for each zone of the three houses are shown graphically. The graphs show 21 days of data: from 5 September 2007 to 26 September 2007. AccuRate simulations used for the empirical validation are based on the 'as-built and site-climate' inputs, incorporating: modification to ventilation parameters, thermostat settings, and infiltration values, as well as the use of site-measured climate data in lieu of AccuRate's in-built TMY climate file. The purpose for presenting the software simulation and measured data in a graphical format is to examine visually whether or not the two data sets have similar temperature profiles. If the profiles are similar, but show different values, AccuRate's heat balance equations for surfaces and spaces are fundamentally acceptable. If the profiles of the two compared values are dissimilar, the software may not be simulating the thermal performance of some surfaces and spaces correctly. The graphical analysis focuses on the following temperature comparisons:

- General temperature range and swings;
- Average temperatures;
- Average minimum temperatures;
- Average maximum temperatures;
- Differences between measured and simulated temperatures (measured – simulated temperatures).

To determine general trends in all three construction types, the graphical analysis involves a limited selection of zones namely:

- Living room;
- Bedroom 1;
- Hallway;
- Roof space;
- Subfloor (for the 5-star and 4-star timber floor house only).

The data for the remaining zones of the garage, bedroom 2 and bathroom are provided in Appendix 3.

8.3.1. The Slab Floor House

a) Living Room

Figure 8.11 shows the comparison of simulated and measured temperatures in the living room of the slab floor house.

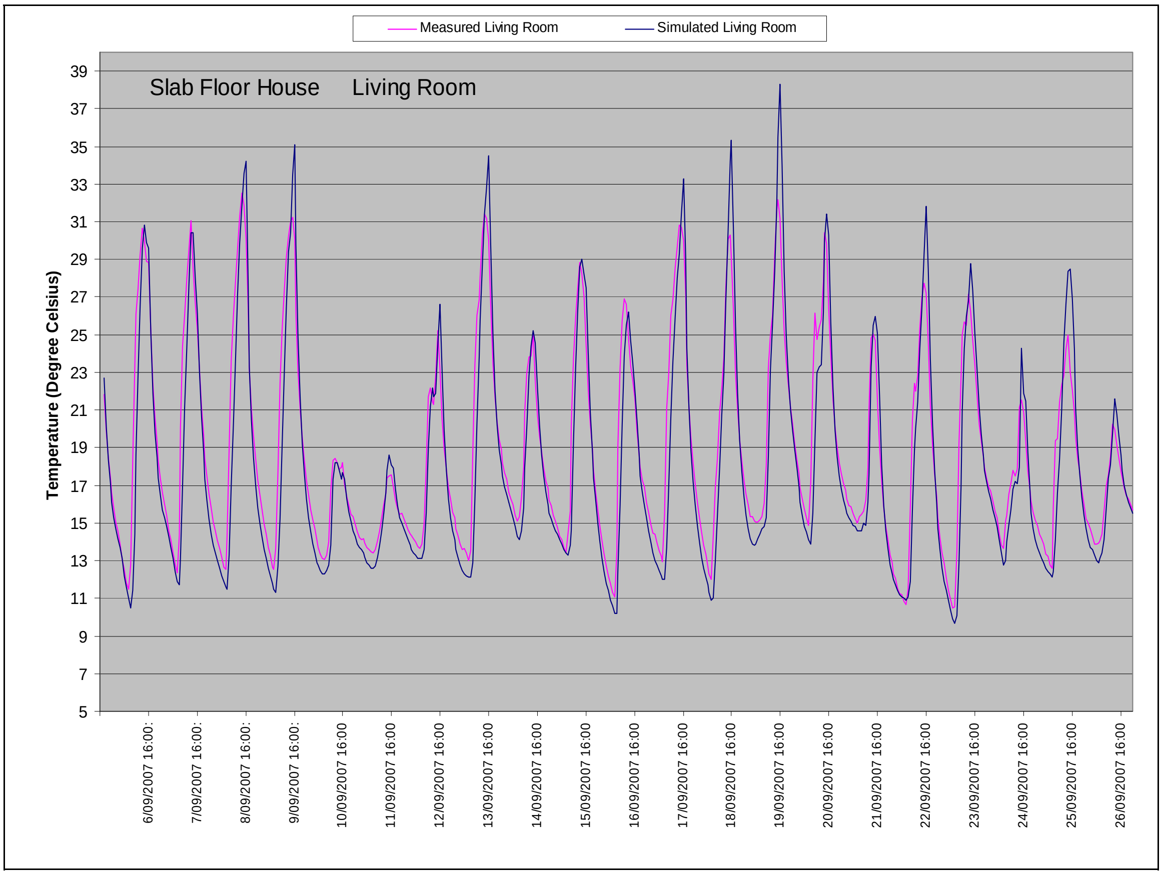


Figure 8.11: Comparison of simulated and measured temperature in the living room of the slab floor house

The temperatures profiles are similar, showing lower minimum, but also higher maximum simulated temperatures, compared to measured temperatures. Table 8.5 summarizes the temperature comparison between the simulated and measured temperatures for the living room of the slab house.

Table 8.5: Comparison of measured and simulated temperatures in the living room of the slab floor house

Description	Simulated Temperatures (ºC)	Measured Temperatures (ºC)	Measured – Simulated Temperatures (Residuals) (ºC) *
Temperature range	9.7-35.1	10.5-32.2	
Average temperature	18.1	18.8	+ 0.7
Average minimum temperature	12.2	13.0	+ 0.8
Average maximum temperature	28.7	26.9	- 1.8

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

The simulated average minimum temperature is 0.8ºC lower and the simulated average maximum temperature 1.8ºC higher compared to the measured value.

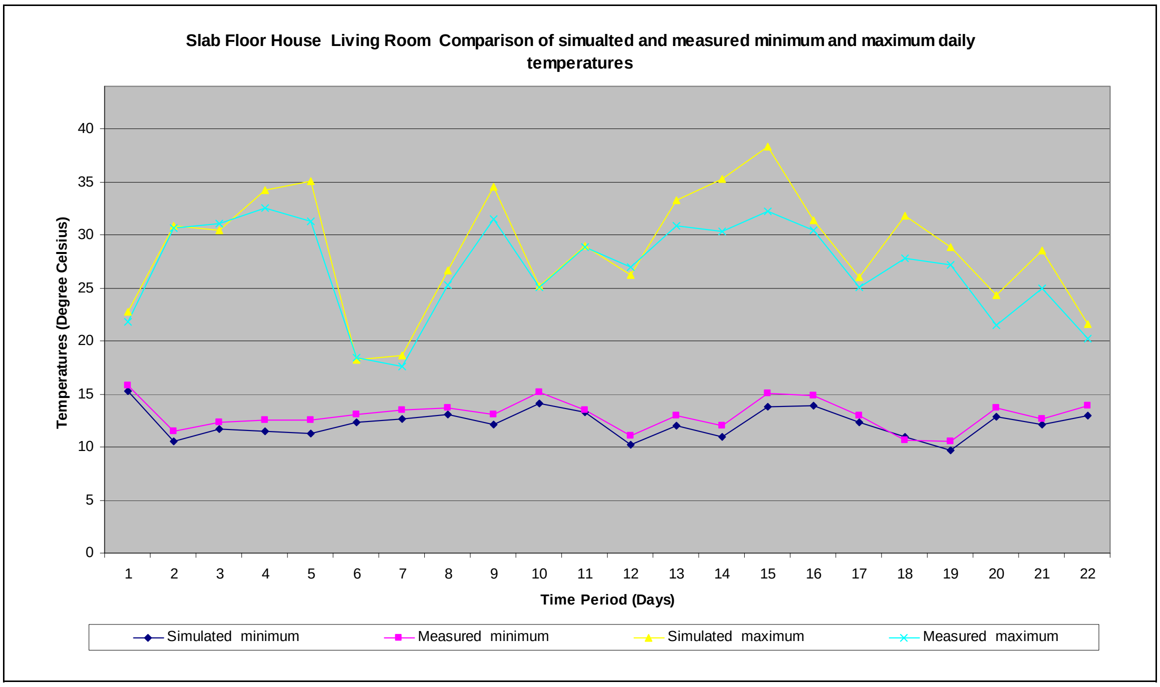


Figure 8.12: Comparison of simulated and measured maximum and minimum daily temperatures in the living room of the slab floor house

Figure 8.12 shows the differences of simulated and measured daily maximum and minimum temperatures for the living room of the slab floor house. While the differences of the minimum temperatures are small, the temperature differences for the maximum simulated temperatures are relatively higher on several days, with a maximum difference of 6.6ºC experienced on Day 15.

b) Bedroom 1

Figure 8.13 shows a comparison of simulated and measured temperature profiles for bedroom 1.

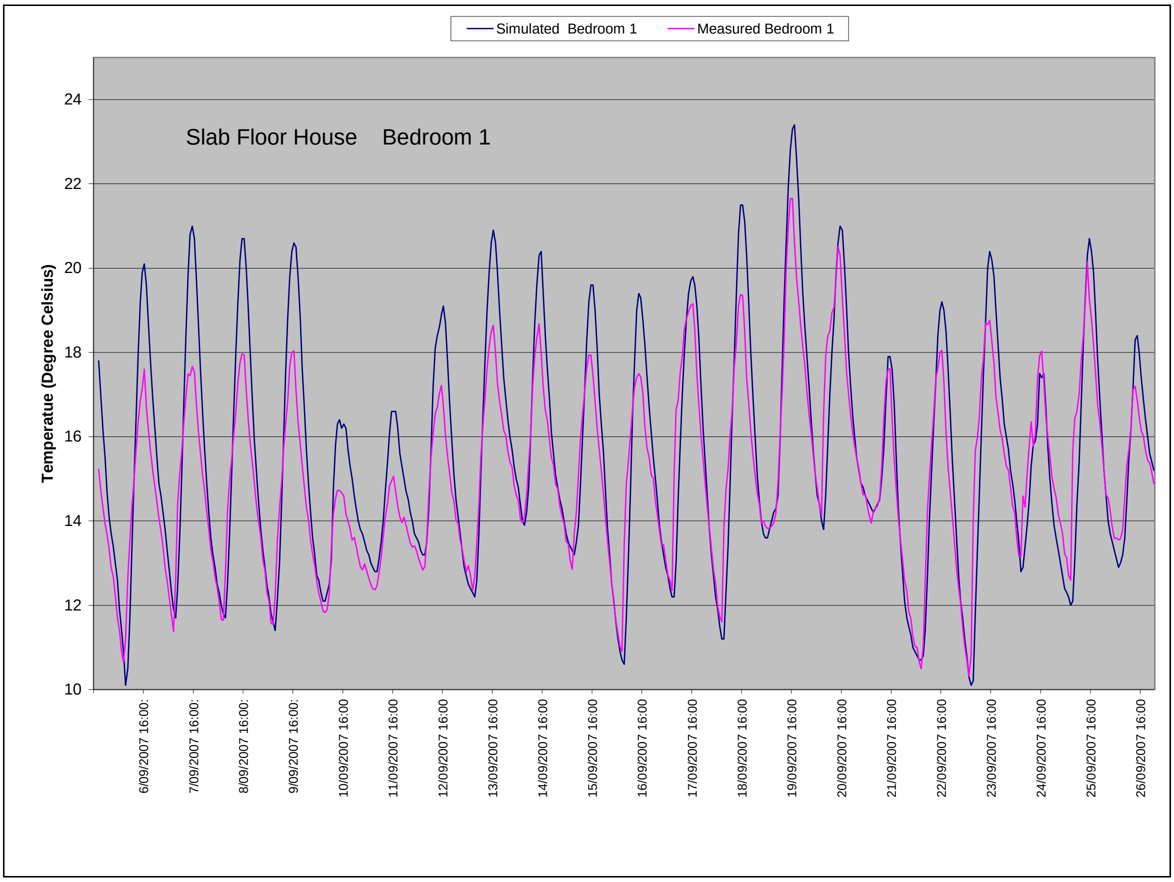


Figure 8.13: Comparison of simulated and measured temperatures in bedroom 1 of the slab floor house

Minimum temperatures are very similar for the simulated and measured values and simulated maximum temperatures are, except on Day 20, constantly higher than the measured values.

Table 8.6: Comparison of measured and simulated temperatures in bedroom 1 of the slab floor house

Description	Simulated Temperatures (ºC)	Measured Temperatures (ºC)	Measured – Simulated Temperatures (Residuals) (ºC) *
Temperature range	10.1-23.4	10.6-21.7	
Average temperature	15.6	15.1	- 0.5
Average minimum temperature	12.2	12.3	+ 0.1
Average maximum temperature	19.7	18.0	- 1.7

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Table 8.6 provides a summary of temperature comparisons for bedroom 1. The simulated average minimum temperature is only 0.1ºC lower and the simulated average maximum temperature is 1.7ºC higher for bedroom 1. Figure 8.14 shows the differences of simulated and measured daily maximum and minimum temperatures for bedroom 1 in the slab floor house.

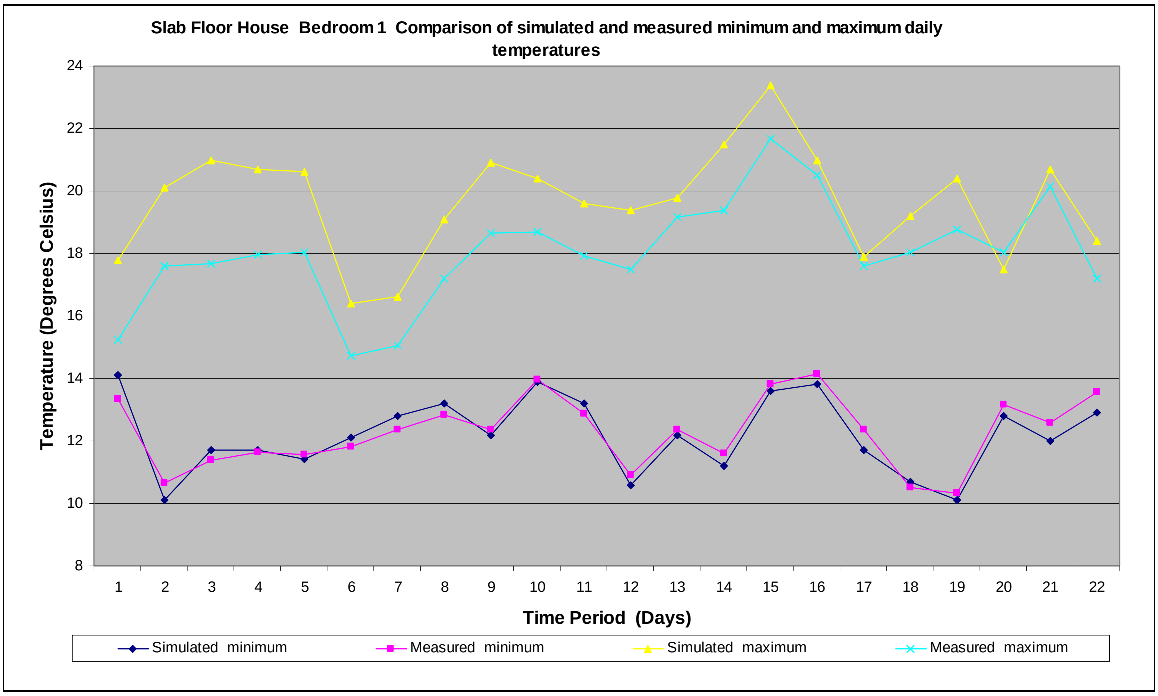


Figure 8.14: Comparison of simulated and measured maximum and minimum daily temperatures in bedroom 1 of the slab floor house

While the minimum simulated temperatures are reasonably similar to the measured values, maximum simulated temperatures are higher, with the largest simulated temperature difference of 3.3ºC was experienced on Day 3.

c) Hallway

Figure 8.15 shows a comparison of simulated and measured temperatures profiles for the hallway.

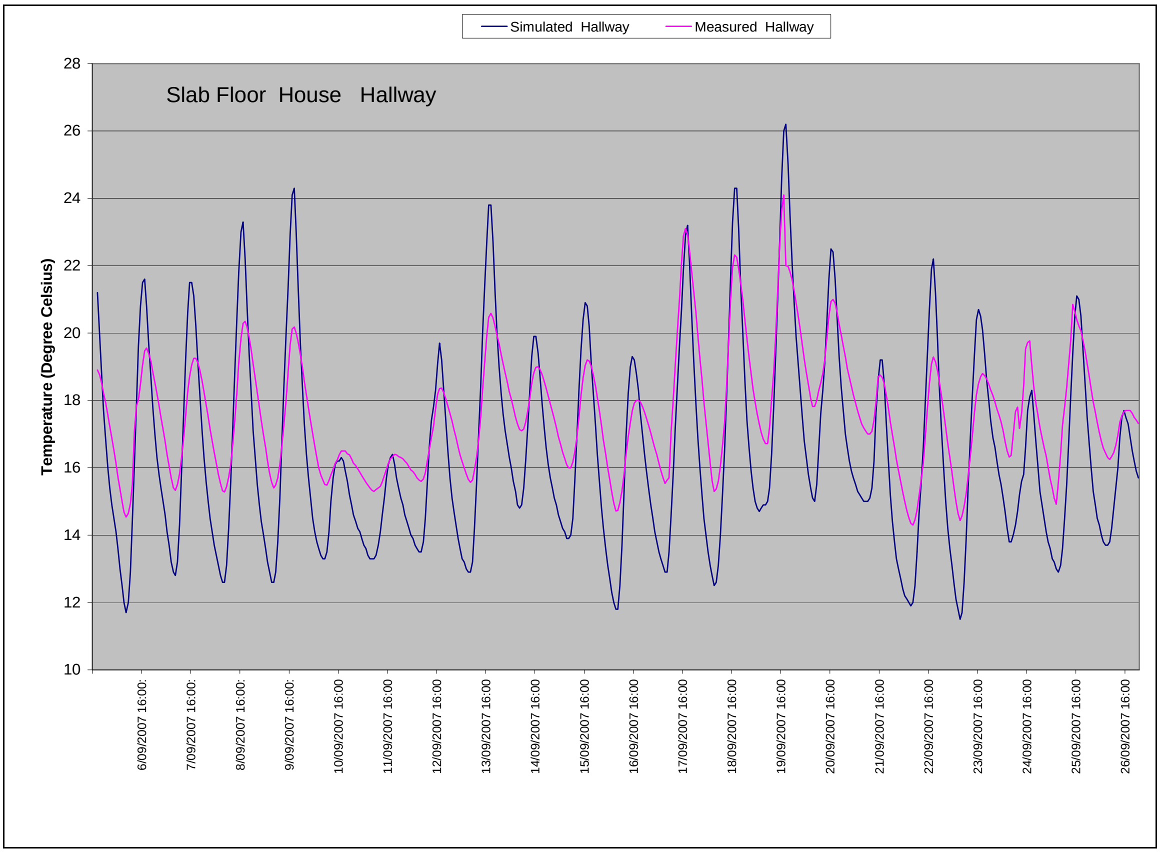


Figure 8.15: Comparison of simulated and measured temperatures in the hallway of the slab floor house

Figure 8.15 shows the profiles of measured and simulated temperatures for the hallway of the slab floor house. Simulated maximum temperatures are higher and simulated minimum temperature lower, compared to the measured values. Table 8.7 provides a summary of the temperature comparisons for the simulated and measured temperature values for the hallway in the slab floor house.

Table 8.7: Comparison of measured and simulated temperatures in the hallway of the slab floor house

Description	Simulated Temperatures (ºC)	Measured Temperatures (ºC)	Measured – Simulated Temperatures (Residuals) (ºC) *
Temperature range	11.7-26.2	14.3-24.1	
Average temperature	16.5	17.6	+ 1.1
Average minimum temperature	13.3	15.7	+ 2.4
Average maximum temperature	21.1	19.7	- 1.4

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

The average simulated average minimum temperature is 2.4ºC lower and the average simulated maximum temperature 1.4ºC higher than the measured values. Figure 8.16 presents the comparison of simulated and measured temperature differences for the hallway.

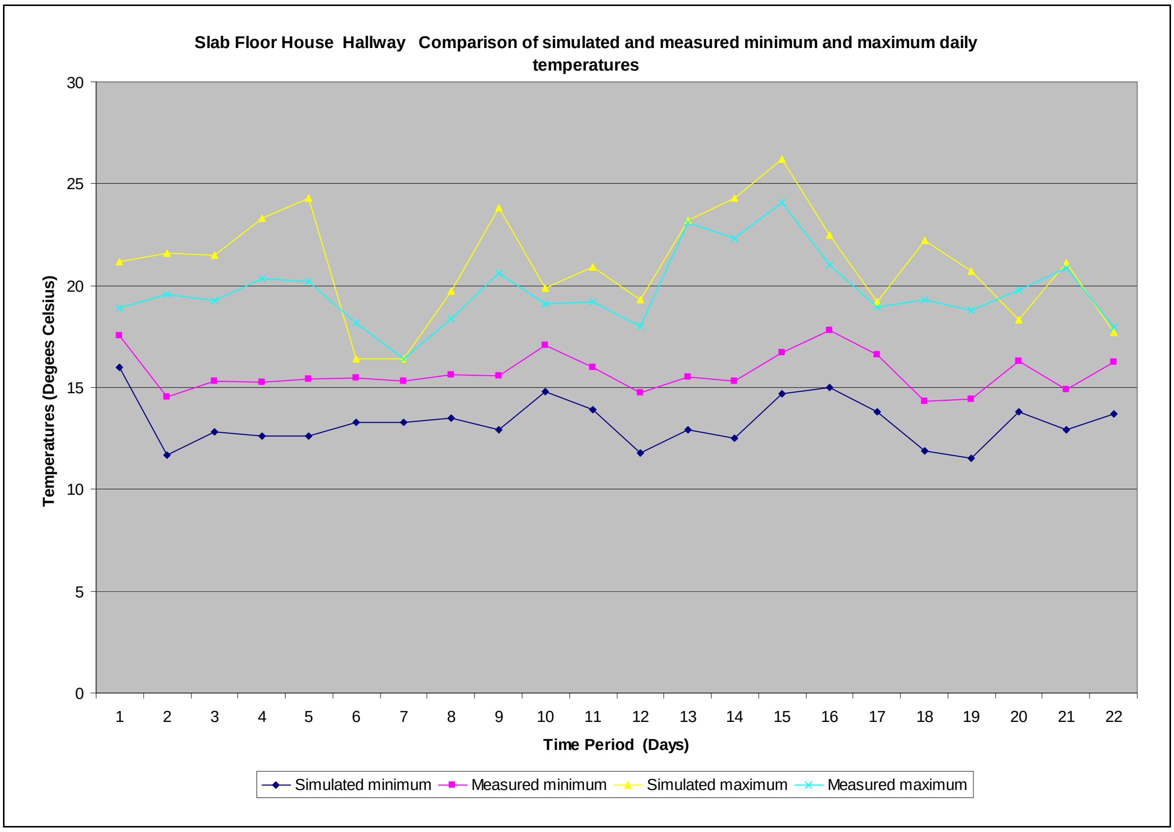


Figure 8.16 Comparison of simulated and measured maximum and minimum daily temperatures in the hallway of the slab floor house

Simulated daily minimum temperatures are constantly between 2ºC and 3ºC lower when compared to the measured temperatures. On some days, simulated maximum temperatures are higher, with 4.2ºC on Day 5, 3.3ºC on Day 9, 2.1ºC on Day 15 and 3ºC higher temperatures simulated on Day 18.

d) Roof space

Figure 8.17 shows the profiles of simulated and measured temperatures for the roof space of the slab floor house.

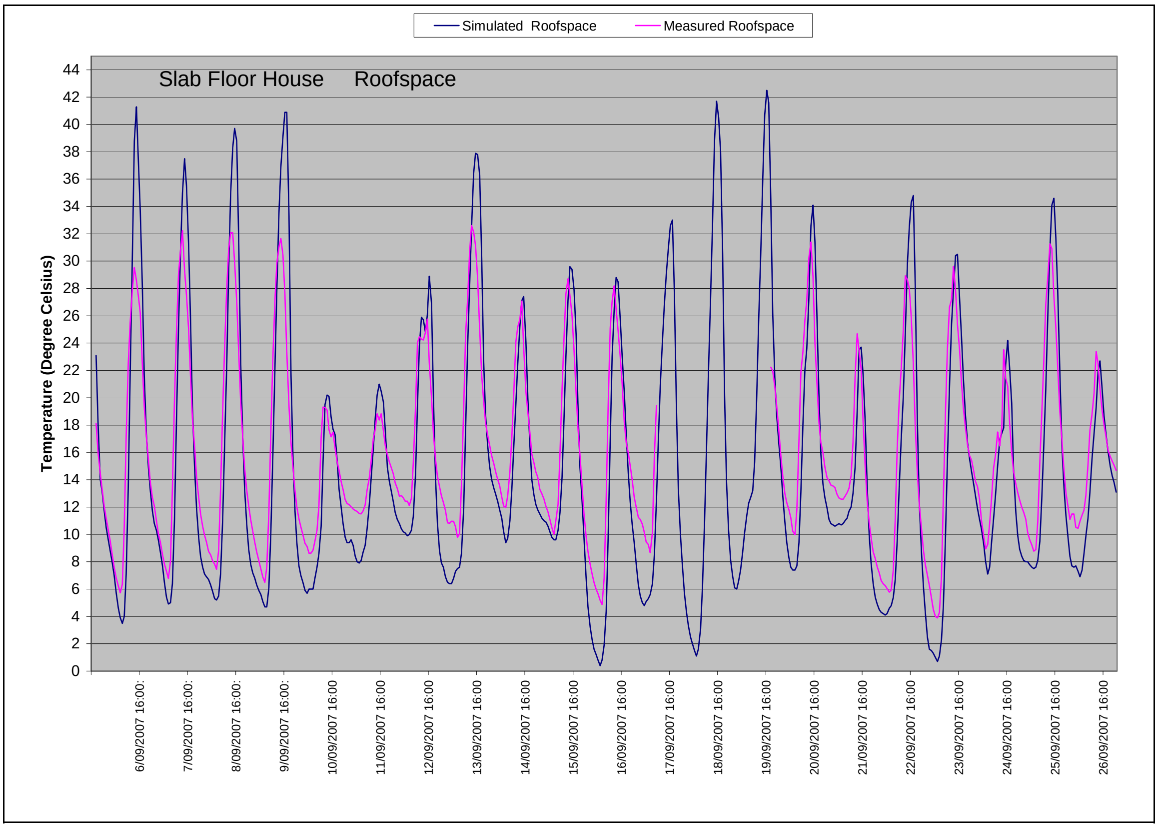


Figure 8.17: Comparison of simulated and measured temperatures in the roof space of the slab floor house

Very high temperatures were simulated and measured in the roof space of the slab floor house. The simulated temperature range is between 0.4ºC and 42.5ºC and between 4.9ºC and 32.6ºC for the measured temperatures. Simulated temperatures are generally higher, but also occasionally lower than measured values. Table 8.8 summarizes a range of temperature comparisons for the roof space.

Table 8.8: Comparison of measured and simulated temperatures in the roof space of the slab floor house

Description	Simulated Temperatures (ºC)	Measured Temperatures (ºC)	Measured – Simulated Temperatures (Residuals) (ºC) *
Temperature range	0.4-42.5	4.9-32.6	
Average temperature	15.2	16.0	+ 0.8
Average minimum temperature	5.5	8.5	+ 3.0
Average maximum temperature	31.7	27.2	- 4.5

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Simulated average minimum temperature is 3ºC lower and average maximum temperature 4.5ºC higher than measured temperatures. Figure 8.18 shows the comparison of simulated and measured daily minimum and maximum temperatures in the roof space.

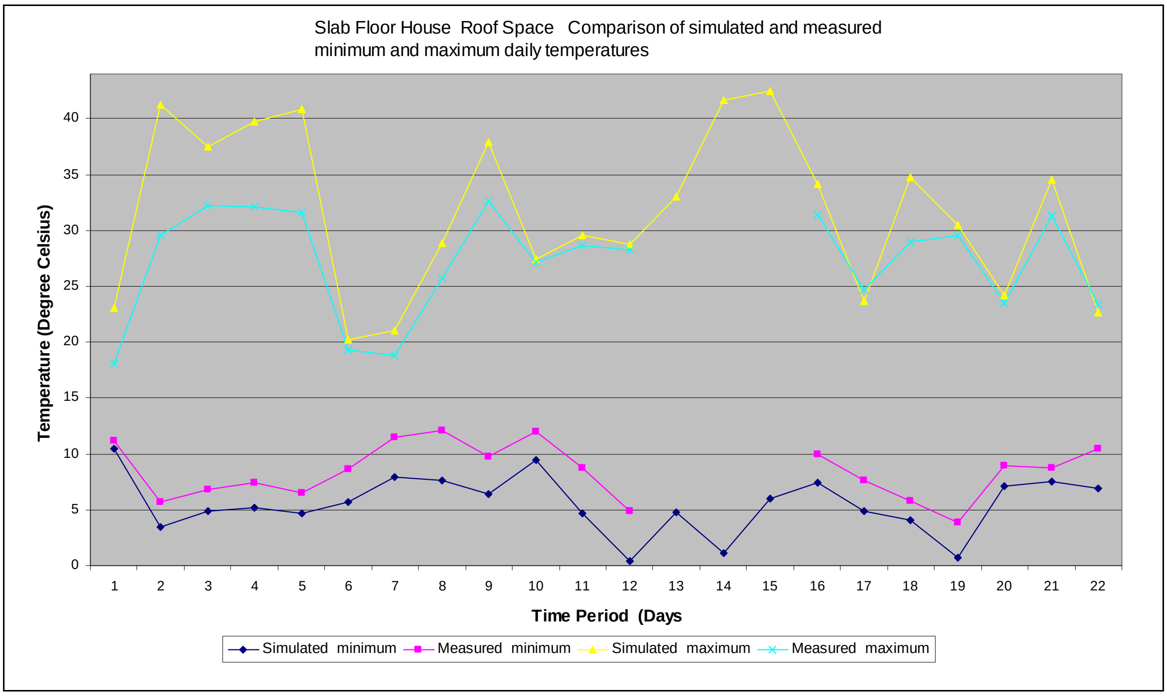


Figure 8.18: Comparison of simulated and measured daily maximum and minimum temperatures in the roof space or the slab floor house

The collection of measured temperatures was interrupted, due to a faulty bell wire connection to the Krone connector between Days 12 and 16. The minimum temperature profiles are reasonably similar and the largest temperature difference was recorded on Day 8, where the simulated temperature was 4.6ºC higher. Simulated maximum temperatures are consistently higher, with the largest temperature difference of 11.8ºC recorded on Day 2.

e) House Zone Temperature Comparisons

Table 8.9 provides a summary of temperature ranges and average minimum and maximum temperature differences for: the living room, bedroom 1, hallway and roof space of the slab floor house.

Table 8.9: Comparison of ranges, average minimum and average maximum measured and simulated temperatures of various zones in the slab floor house

	Type of Measured Temperature					
Zone	Simulated Average Minimum Temperature (ºC)	Measured Average Minimum Temperature (ºC)	Difference (Measured Average Minimum – Simulated Average Minimum Temperature) (ºC) *	Simulated Average Maximum Temperature (ºC)	Measured Average Maximum Temperature (ºC)	Difference (Measured Average Maximum – Simulated Average Maximum Temperature (C) *
Living Room	12.2	13.0	+ 0.7	28.7	26.9	- 1.8
Bedroom 1	12.2	12.3	+ 0.1	19.7	18.0	- 1.7
Hallway	13.3	15.7	+ 2.4	21.1	19.7	- 1.4
Roof space	5.5	8.0	+ 3.0	31.7	27.2	- 4.5

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Table 8.9 shows that AccuRate simulations consistently under-and over-predicted average minimum and maximum temperatures respectively in the slab floor house. Simulated average under-predicted temperatures are lower in bedroom 1 (0.1ºC) and in the living room (0.7ºC). In the hallway and the roof space average under-predicted temperatures are higher with 2.4ºC in the hallway and 3.0ºC in the roof-space. Simulated average over-predicted temperatures range between 1.8ºC and 1.7ºC in the living room, bedroom 1 and the hallway. By far the highest simulated over-predicted average temperature of 4.5ºC is recorded in the roof space.

8.3.2. The 5-Star Timber Floor House

a) Living Room

Figure 8.19 shows the measured and simulated temperature profiles in the living room of the 5-star timber floor house.

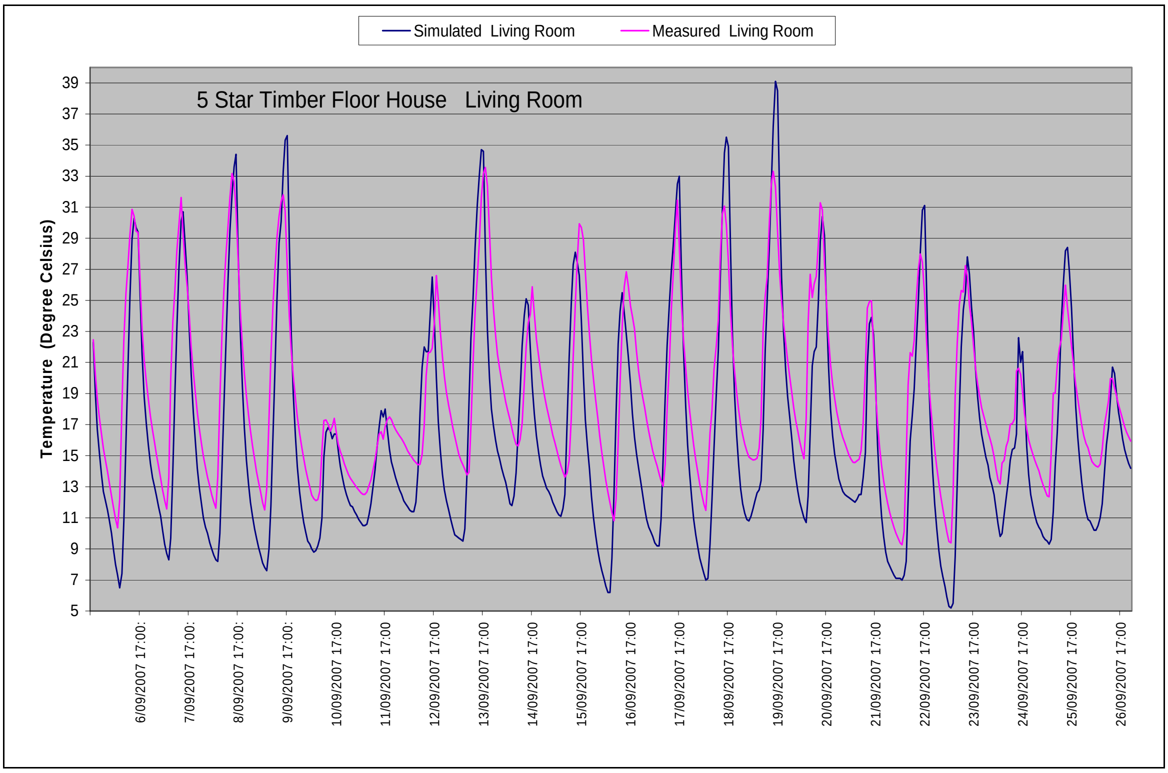


Figure 8.19: Comparison of simulated and measured temperatures in the living room of the 5-star timber floor house

Temperature profiles are reasonably similar, showing higher maximum simulated temperatures on most days, but consistently lower minimum simulated temperatures. Table 8.10 provides a summary of temperatures for the living room of the 5-star timber floor house.

Table 8.10: Comparison of measured and simulated temperatures in the living room of the 5-star timber floor house

Description	Simulated Temperatures (ºC)	Measured Temperatures (ºC)	Measured – Simulated Temperatures (Residuals) (ºC) *
Temperature range	5.2-39.1	9.3-33.6	
Average temperature	16.3	18.9	+ 2.6
Average minimum temperature	9.0	12.6	+ 3.6
Average maximum temperature	28.2	27.3	- 0.9

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

The average simulated maximum temperature is 0.9ºC higher, but the minimum temperature, is a noteworthy 3.6ºC lower then the measured temperature. The simulated average temperature is 2.6ºC lower than the measured average temperature. Figure 8.20 illustrates the differences between simulated and measured daily maximum and minimum temperatures for the living room.

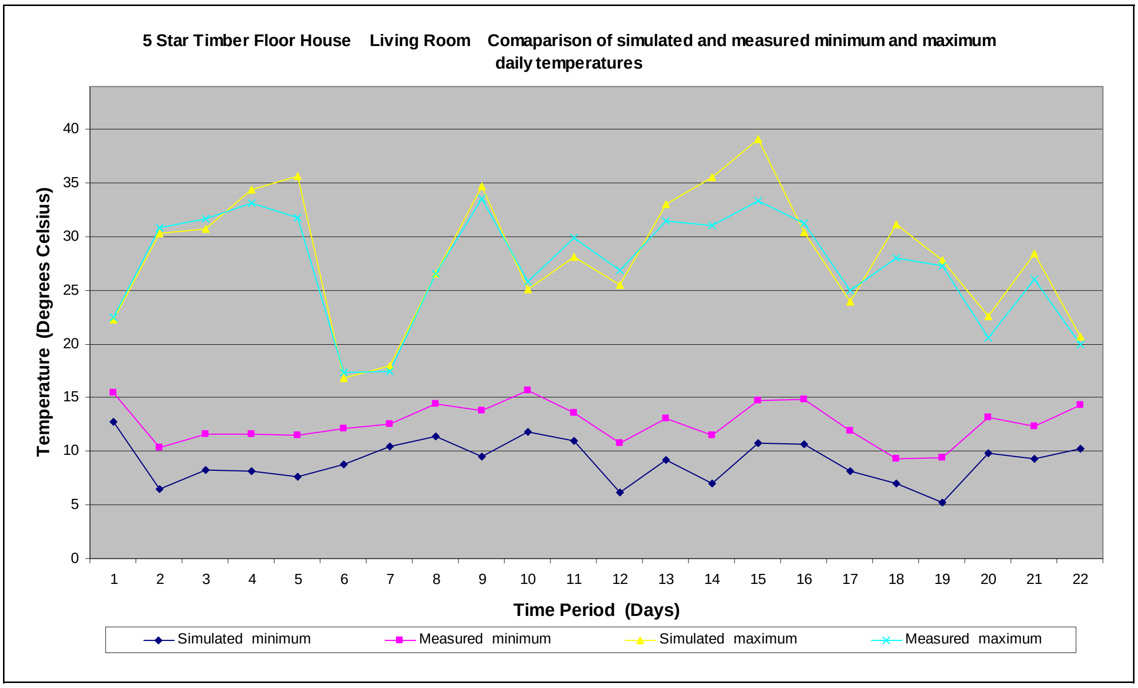


Figure 8.20: Comparison of simulated and measured daily minimum and maximum temperatures in the living room of the 5-star timber floor house

The simulated minimum daily temperatures are always between 2ºC and 4ºC lower than the measured values. Simulated maximum temperatures are reasonably similar on most days, except on Days 5, 14, 15 and 18, when temperatures were higher by up to 5.8ºC.

b) Bedroom 1

Figure 8.21 shows the temperature profiles of simulated and measured values for bedroom 1. The temperature profile differs from the temperature profile in bedroom 1 of the slab floor house, showing higher and lower simulated temperatures compared to the measured temperatures. The lesser temperature swings in bedroom 1 of the slab floor house could be due to the thermal mass of the concrete slab floor, even when carpeted over.

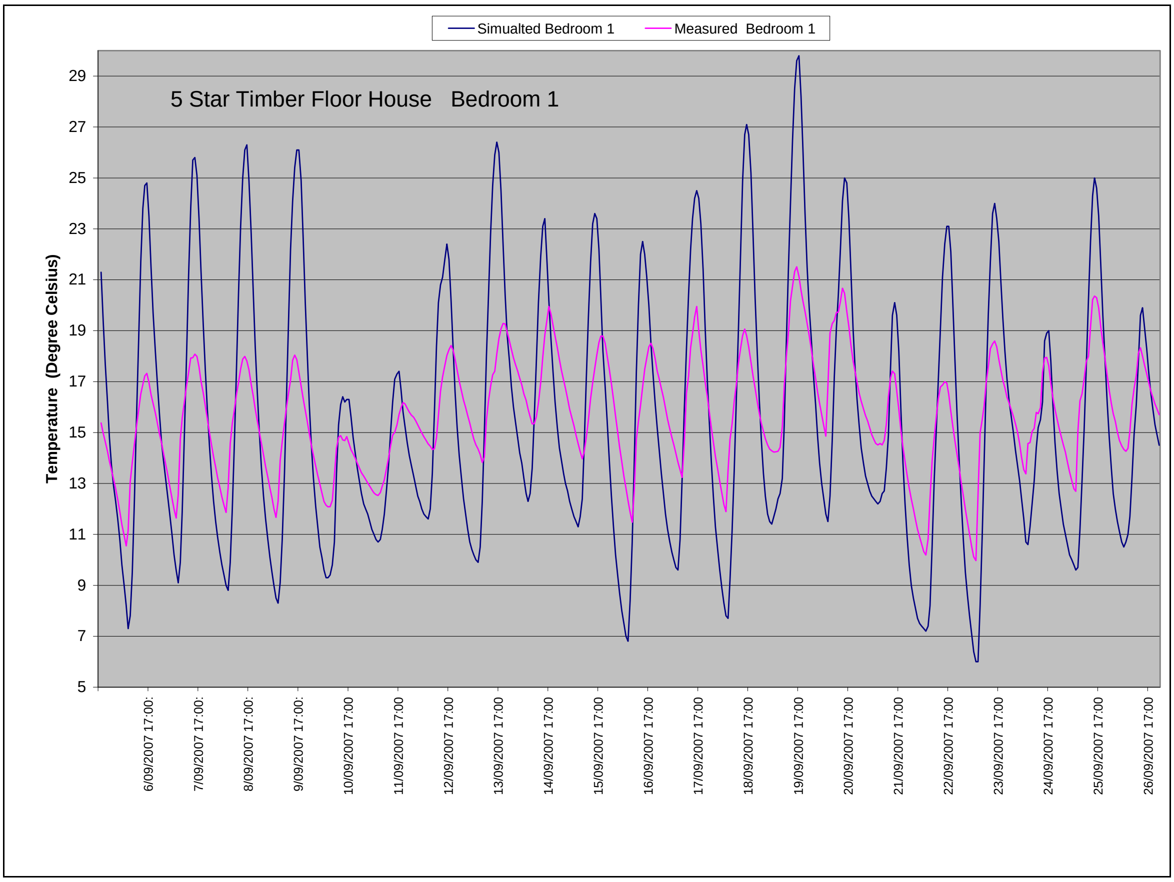


Figure 8.21: Comparison between simulated and measured temperatures in bedroom 1 of the 5-star timber floor house

Table 8.11: Comparison of measured and simulated temperatures in the bedroom of the 5-star timber floor house

Description	Simulated Temperatures (ºC)	Measured Temperatures (ºC)	Measured – Simulated Temperatures (Residuals) (ºC) *
Temperature range	6-29.8	10.0-21.5	
Average temperature	15.6	15.6	0.0
Average minimum temperature	9.6	12.7	+ 3.1
Average maximum temperature	23.4	18.3	- 5.5

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Table 8.11 includes the summary of temperature comparison for bedroom 1of the 5-star timber floor house. It is worthwhile to note, that while the average temperatures are the same for the simulated measured values, the differences of the average maximum and minimum temperatures vary considerably. The simulated maximum average temperature is 5.5ºC higher, while the minimum average temperature is 3.1ºC lower, compared to the measured values. Figure 8.22 illustrates the comparison of average daily minimum and maximum simulated and measured temperatures.

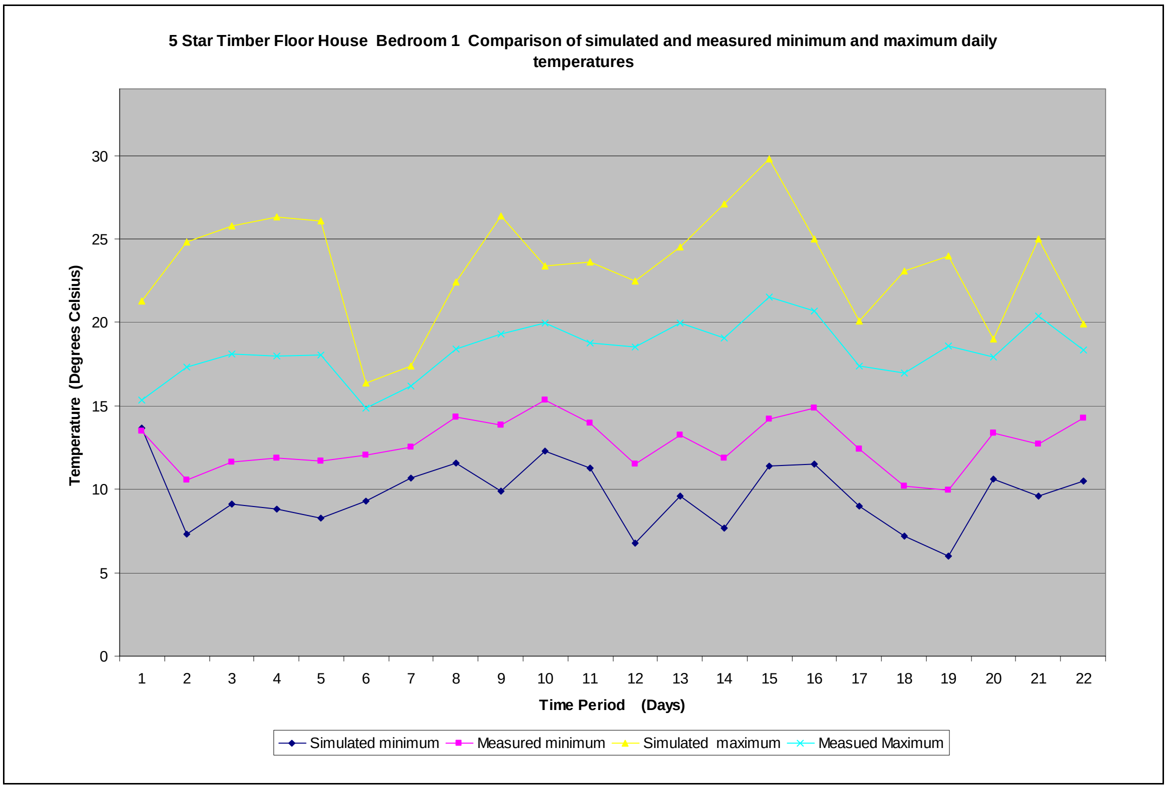


Figure 8.22: Comparison of simulated and measured daily maximum and minimum temperatures in bedroom 1 of the 5-star timber floor house

Simulated minimum temperatures are between 2.5ºC and 3.9ºC lower and simulated maximum temperatures are up to 8.4ºC higher than the measured values.

c) Hallway

Figure 8.23 presents the comparison of simulated and measured temperature profiles for the hallway.

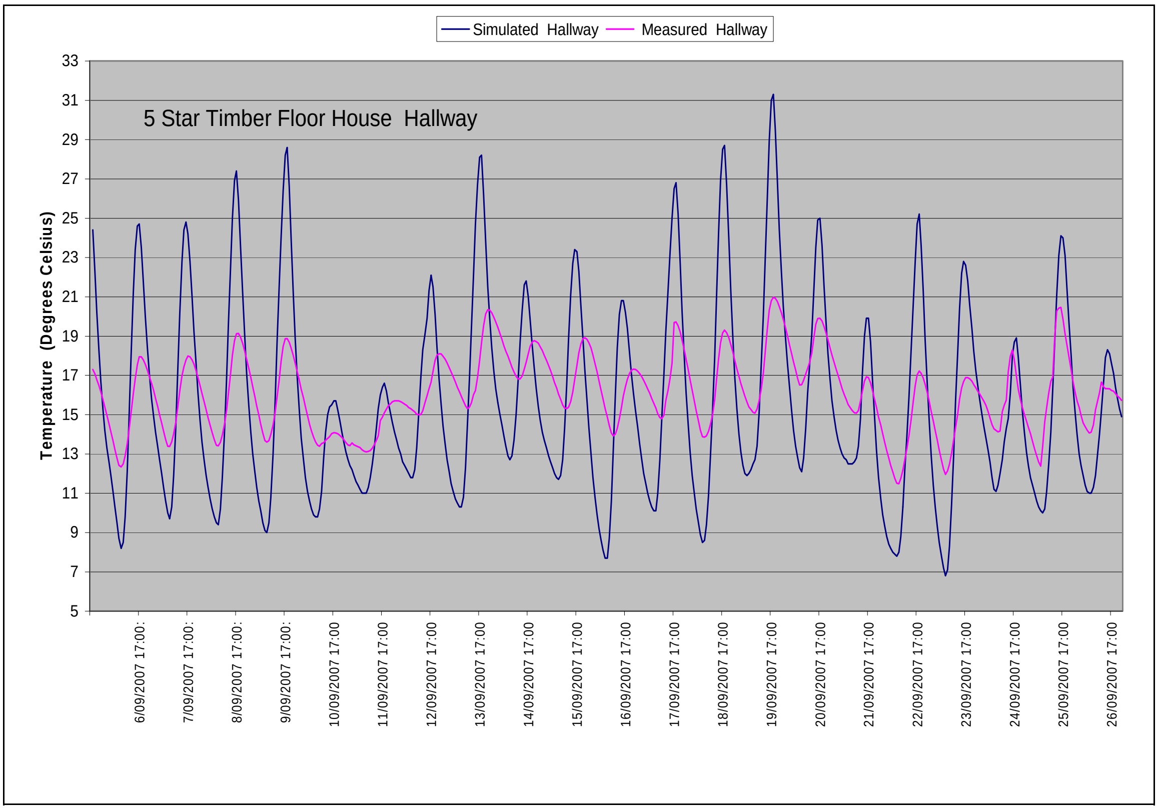


Figure 8.23: Comparison of simulated and measured temperatures in the hallway of the 5-star timber floor house

As in bedroom 1 of the slab floor house, temperature profiles are dissimilar, showing significant higher and lower simulated temperatures. Table 8.12 presents the summary of temperature comparisons. While the average temperature values are similar for the simulated and measured values, there are large differences between the average minimum and maximum temperatures between simulated and measured values. The simulated average maximum temperature is 5.1ºC higher and the average minimum temperature 4.0ºC lower.

Table 8.12: Comparison of measured and simulated temperatures in the hallway of the 5-star timber floor house

Description	Simulated Temperatures (ºC)	Measured Temperatures (ºC)	Measured – Simulated Temperatures (Residuals) (ºC) *
Temperature range	6.8-31.3	11.5-21.0	
Average temperature	15.7	16.1	+ 0.4
Average minimum temperature	10.0	14.0	+ 4.0
Average maximum temperature	23.6	18.5	- 5.1

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Figure 8.24 illustrates the daily maximum and minimum temperatures in the hallway of the 5-star timber floor house.

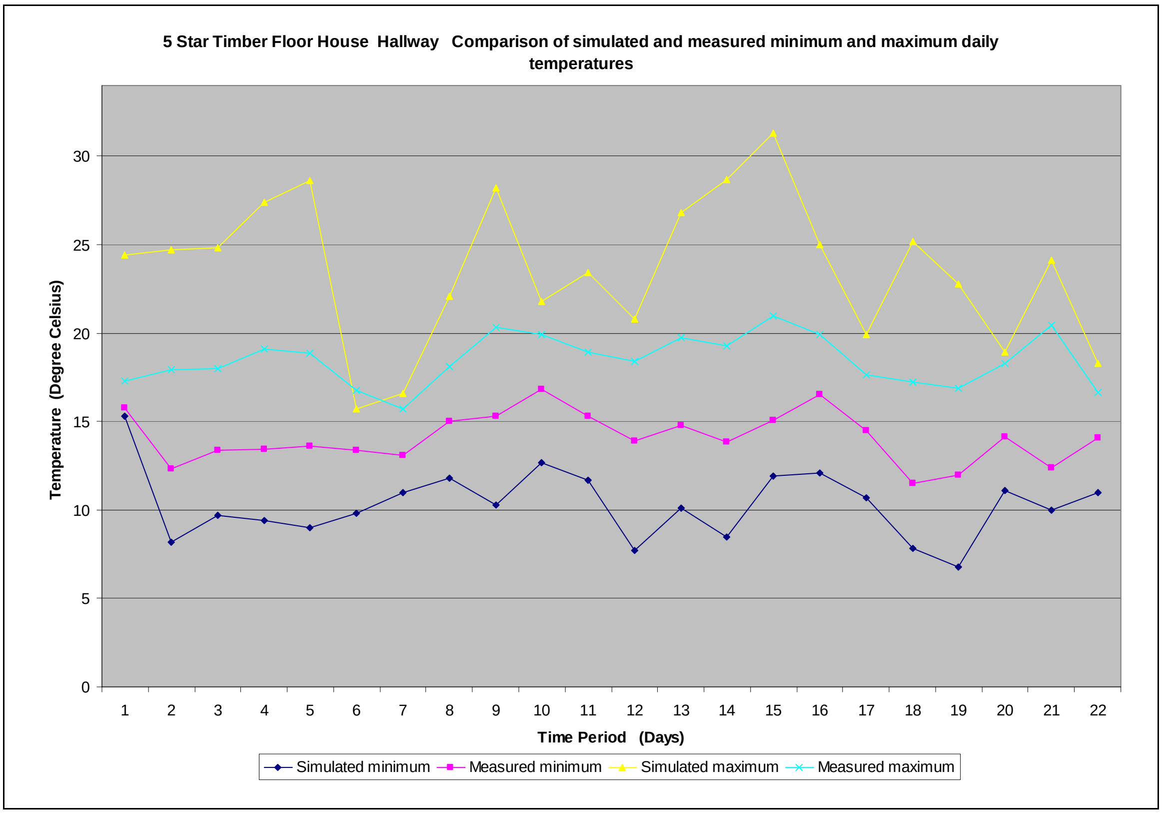


Figure 8.24: Comparison of simulated and measured daily maximum and minimum temperatures in the hallway of the 5-star timber floor house

Minimum simulated daily temperatures are between 2.1ºC and 4.7ºC cooler than measured temperatures. Conversely, simulated maximum daily temperatures are significantly higher than measured values, with the largest temperature difference of 10ºC recorded on Day 15.

d) Roof space

Figure 8.25 shows the profile of simulated and measured temperatures in the roof space of the 5-star timber floor house.

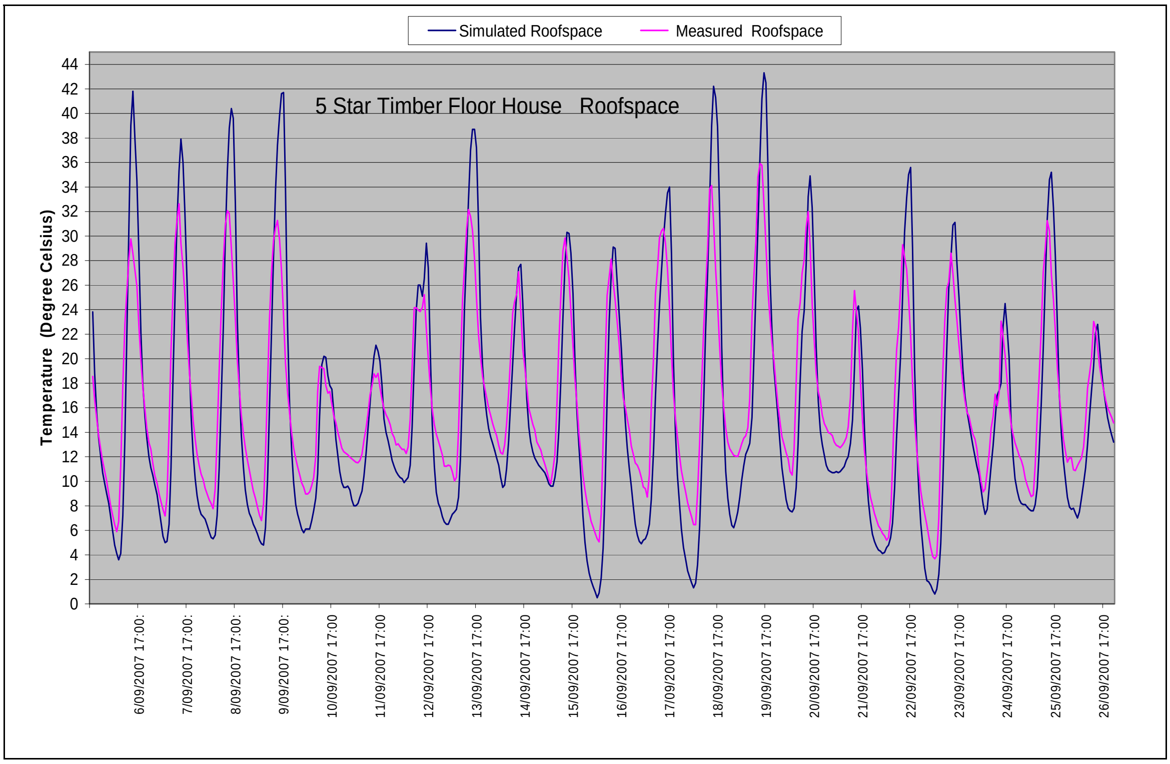


Figure 8.25: Comparison of simulated and measured temperatures in the roof space of the 5-star timber floor house

Temperature profiles for the roof space are generally similar. However, simulated temperatures were generally greater and lower than the measured values. Table 8.13 shows the summary of temperature comparison for the roof space.

Table 8.13: Comparison of measured and simulated temperatures in the roof space of the 5-star timber floor house

Description	Simulated Temperatures (ºC)	Measured Temperatures (ºC)	Measured – Simulated Temperatures (Residuals) (ºC) *
Temperature range	0.5-43.3	3.7-35.9	
Average temperature	15.5	16.6	+ 1.1
Average minimum temperature	5.7	8.7	+ 3.0
Average maximum temperature	32.7	28.1	- 4.6

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

The simulated temperature range of 0.5ºC to 43.3ºC is considerably larger than the measured temperature range of 3.7ºC to 35.9ºC. The average simulated minimum temperature is 3ºC lower and the simulated average maximum temperature 4.6ºC higher. The simulated average temperature is 1.1ºC cooler. Figure 8.26 shows the daily maximum and minimum temperatures in the roof space.

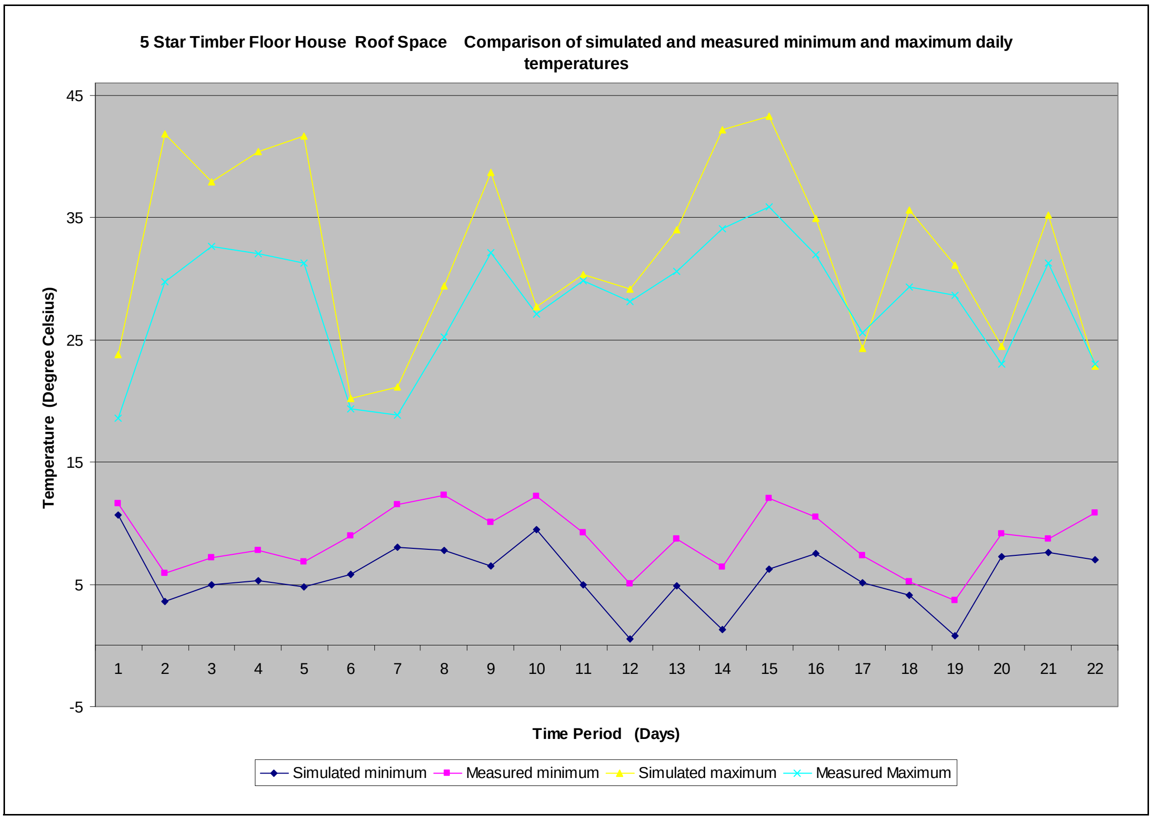


Figure 8.26: Comparison of simulated and measured daily maximum and minimum temperatures in the roof space

Simulated minimum temperatures are generally between 1.8ºC and 5.8ºC lower than the measured values. Simulated maximum temperatures are also up to 10.4ºC higher (on Day 5) but very similar on 7 days, with only 0.8ºC difference recorded on Day 6.

e) Subfloor

Figure 8.27 shows the comparison of simulated and measured temperatures for the subfloor of the 5-star timber floor house.

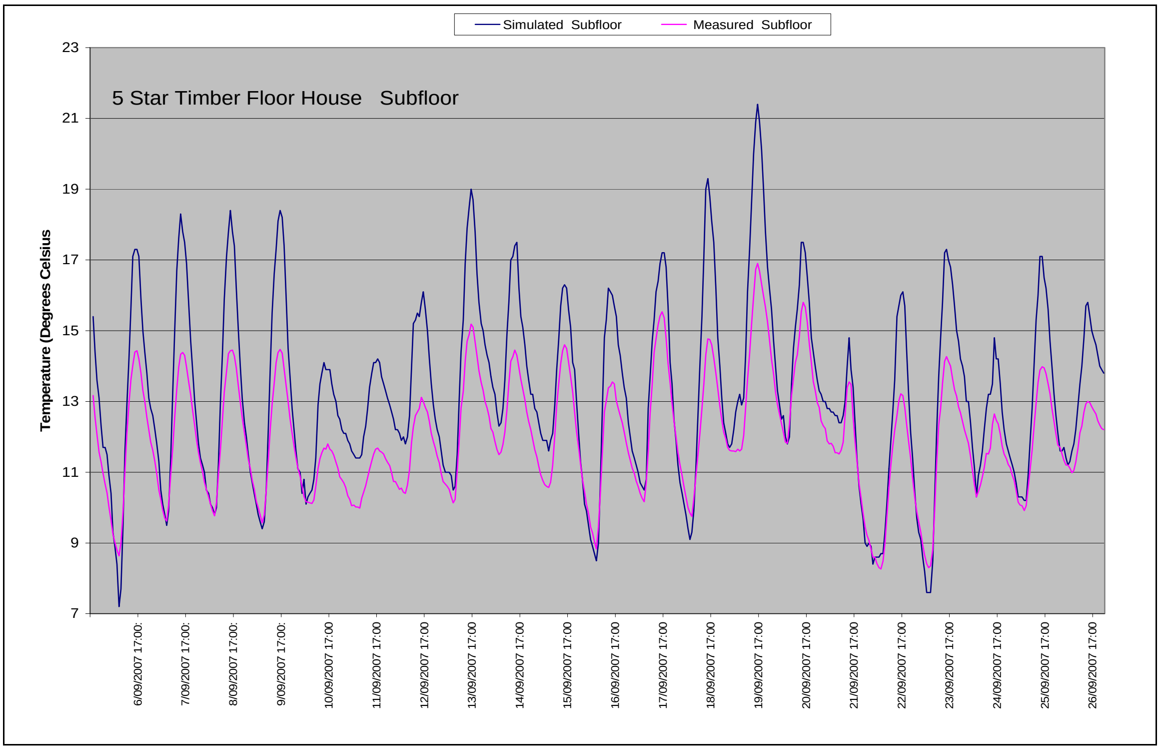


Figure 8.27: Comparison of simulated and measured temperatures in the subfloor of the 5-star timber floor house

Figure 8.27 presents the temperature profiles' comparison for the subfloor of the 5-star timber floor house. Maximum simulated temperatures are always higher, while minimum simulated temperatures are similar, except on two days, (10 and 11 September), where minimum temperatures measured are actually higher than simulated values. Table 8.14 illustrates the summary of temperature comparisons for the subfloor.

Table 8.14: Comparison of measured and simulated temperatures in the subfloor of the 5-star timber floor house

Description	Simulated Temperatures (ºC)	Measured Temperatures (ºC)	Measured – Simulated Temperatures (Residuals) (ºC) *
Temperature range	7.2-21.4	8.3-16.9	
Average temperature	13.3	12.0	- 1.3
Average minimum temperature	10.1	10.0	- 0.1
Average maximum temperature	16.9	14.0	+ 2.9

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

The average minimum temperatures are similar, with only 0.1ºC differences between the two variables. Average simulated maximum temperature is 2.9ºC higher. Figure 8.28 shows the daily maximum and minimum temperatures for the subfloor.

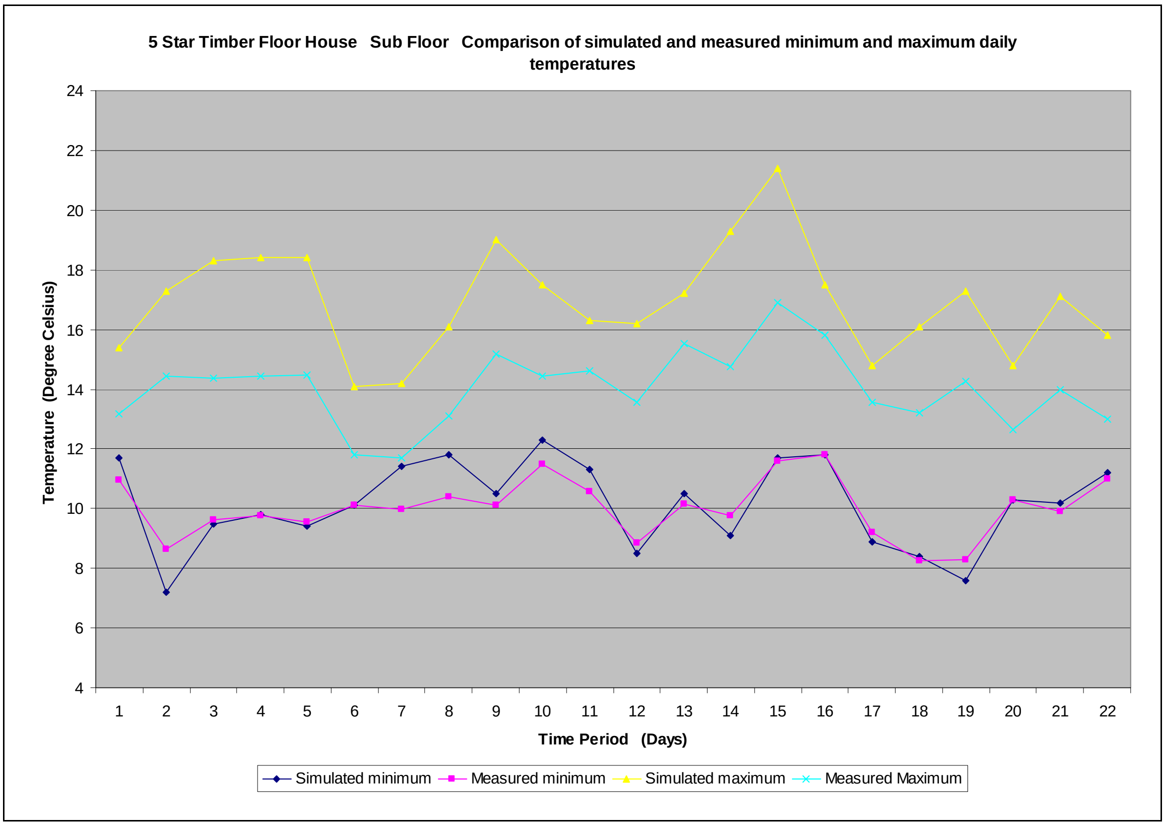


Figure 8.28: Comparison of simulated and measured daily maximum and minimum temperatures in the subfloor

Minimum simulated temperatures are up to 1.4ºC lower on Day 2, but also up to 1.4ºC warmer on Days 7 and 8. Maximum simulated temperatures are constantly between 1.3ºC and 4.5ºC higher than the measured values.

f) House Zone Temperature Comparisons

Table 8.15 compares temperature ranges and temperature of minimum and maximum temperatures for simulated and measured values.

Table 8.15: Comparison of ranges, average minimum and average maximum measured and simulated temperatures of the 5-star timber floor house

	Type of Measured Temperature					
Zone	Simulated Average Minimum Temperature (ºC)	Measured Average Minimum Temperature (ºC)	Difference (Minimum Measured – Minimum Simulated Temperature) (ºC) *	Simulated Average Maximum Temperature (ºC)	Measured Average Maximum Temperature (ºC)	Difference (Maximum Measured – Maximum Simulated Temperature (C) *
Living Room	9.0	12.6	+ 3.6	28.2	27.3	- 0.9
Bedroom 1	9.6	12.7	+ 3.1	23.4	18.3	- 5.5
Hallway	10.0	14.0	+ 4.0	23.6	18.5	- 5.1
Roof Space	5.7	8.7	+ 3.0	32.7	28.1	- 4.6
Subfloor	10.1	10.0	- 0.1	16.9	14.0	+ 2.9

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Table 8.15 shows that AccuRate simulations, with the exception of the sub floor, always under-predicted average minimum temperatures and over-predicted average maximum temperatures. The behaviour of these two variables is similar in the living room but dissimilar in the hallway. Similar temperature predictions are also experienced in the subfloor, where simulated average minimum predictions are within 0.1ºC of the measured value. The largest difference in the simulated and measured temperature occurs in bedroom 1, where the maximum average simulated temperature is 5.5ºC higher compared to the measured value.

8.3.3. The 4-Star Timber Floor House

a) Living Room

Figure 8.29 shows the profile of the measured and simulated temperatures in the living room for the 4-star timber house.

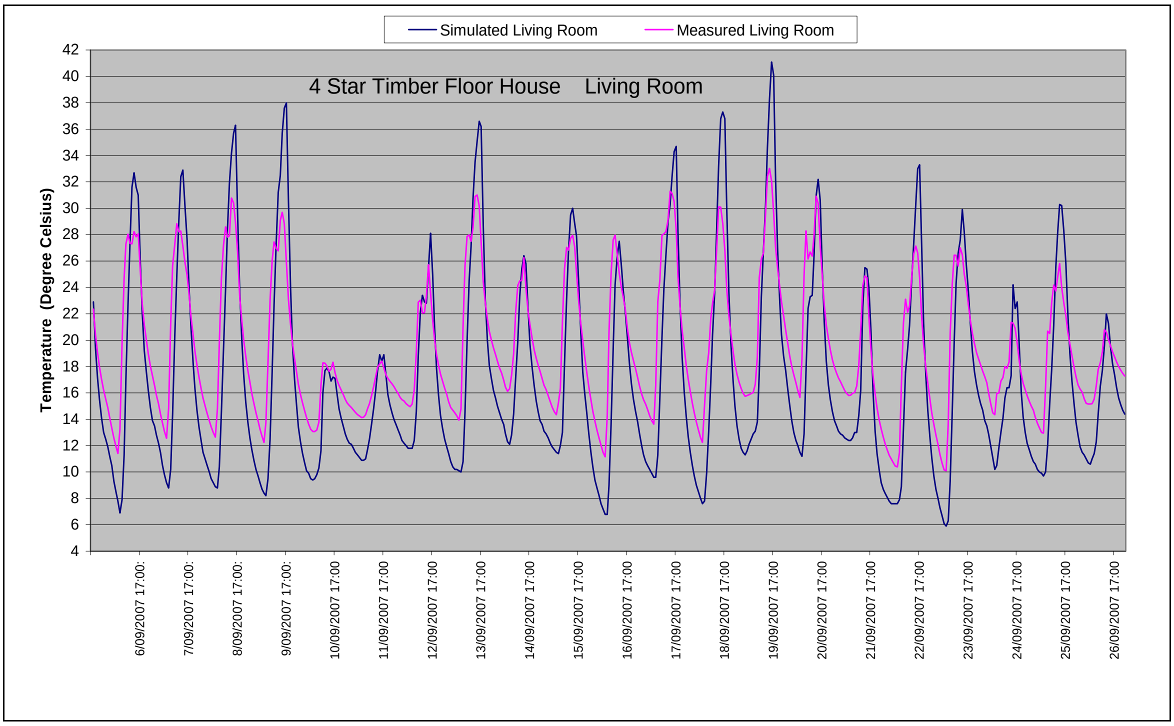


Figure 8.29: Comparison of simulated and measured temperatures in the living room of the 4-star timber floor house

In general, the temperature profiles are similar. However, simulated temperatures in most cases show higher maximum temperatures and in all cases lower minimum temperatures. Table 8.16 presents a summary of temperature comparisons for the living room of the 4-star timber floor house.

Table 8.16: Comparison of measured and simulated temperatures in the living room of the 4-star timber floor house

Description	Simulated Temperatures (ºC)	Measured Temperatures (ºC)	Measured – Simulated Temperatures (Residuals) (ºC) *
Temperature range	5.9 – 41.1	10.3-33.0	
Average temperature	17.1	19.4	+ 2.3
Average minimum temperature	9.6	13.4	+ 3.8
Average maximum temperature	29.9	26.7	- 3.2

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

The simulated and measured temperature ranges differ, showing a simulated range of 5.9ºC to 41.1ºC and a measured range of 10.1ºC to 33.0ºC. The simulated average minimum temperature is 3.8ºC lower and the average maximum temperature 3.2ºC higher than the measured values. Figure 8.30 shows the daily maximum and minimum temperatures of the living room.

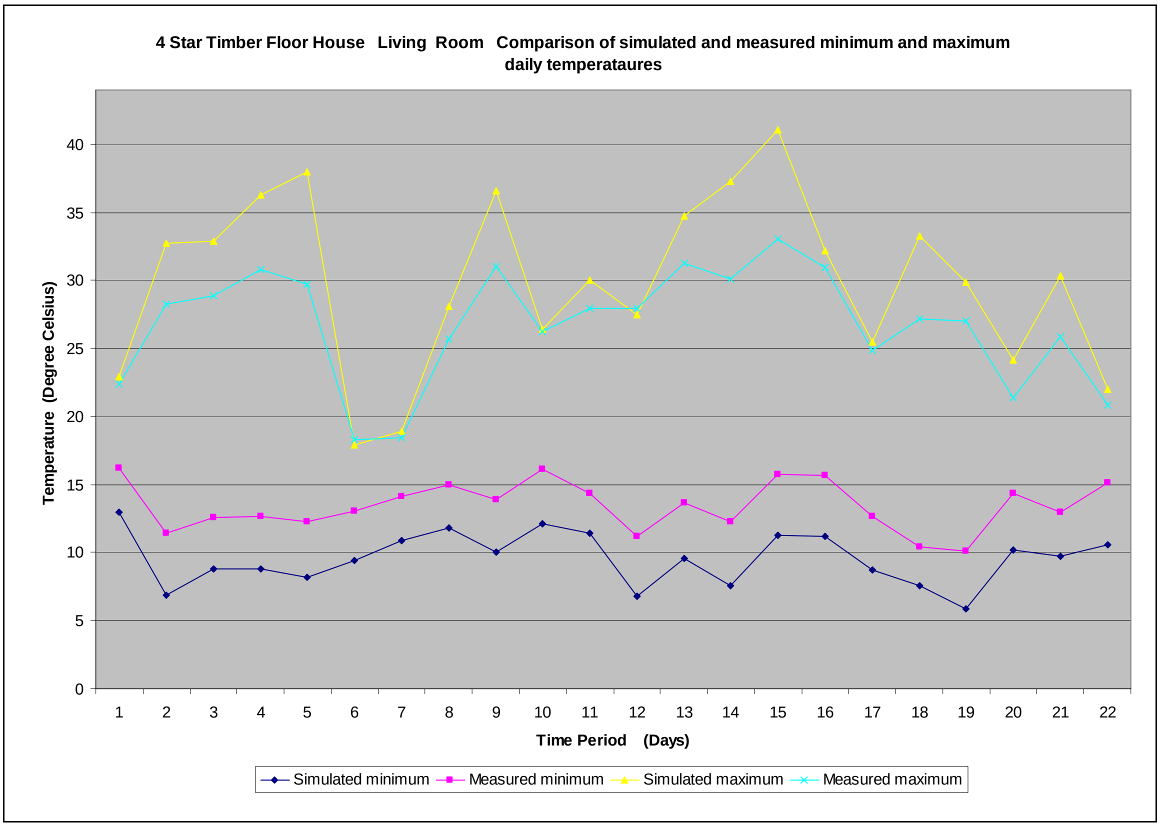


Figure 8.30: Comparison of simulated and measured daily maximum and minimum temperatures in the living room of the 4-star timber floor house

Simulated minimum temperatures are between 3.2ºC and 4.4ºC lower than the measured temperatures, and the maximum simulated temperatures are up to 8.3ºC higher compared to the measured values. The maximum simulated temperatures are very similar on 5 days, with a 0ºC difference recorded for Day 10 and a 0.4ºC difference for Days 5, 7, 12 and 17.

b) Bedroom 1

Figure 8.31 shows the profiles of simulated and measured temperatures for bedroom 1 of the 4-star timber floor house.

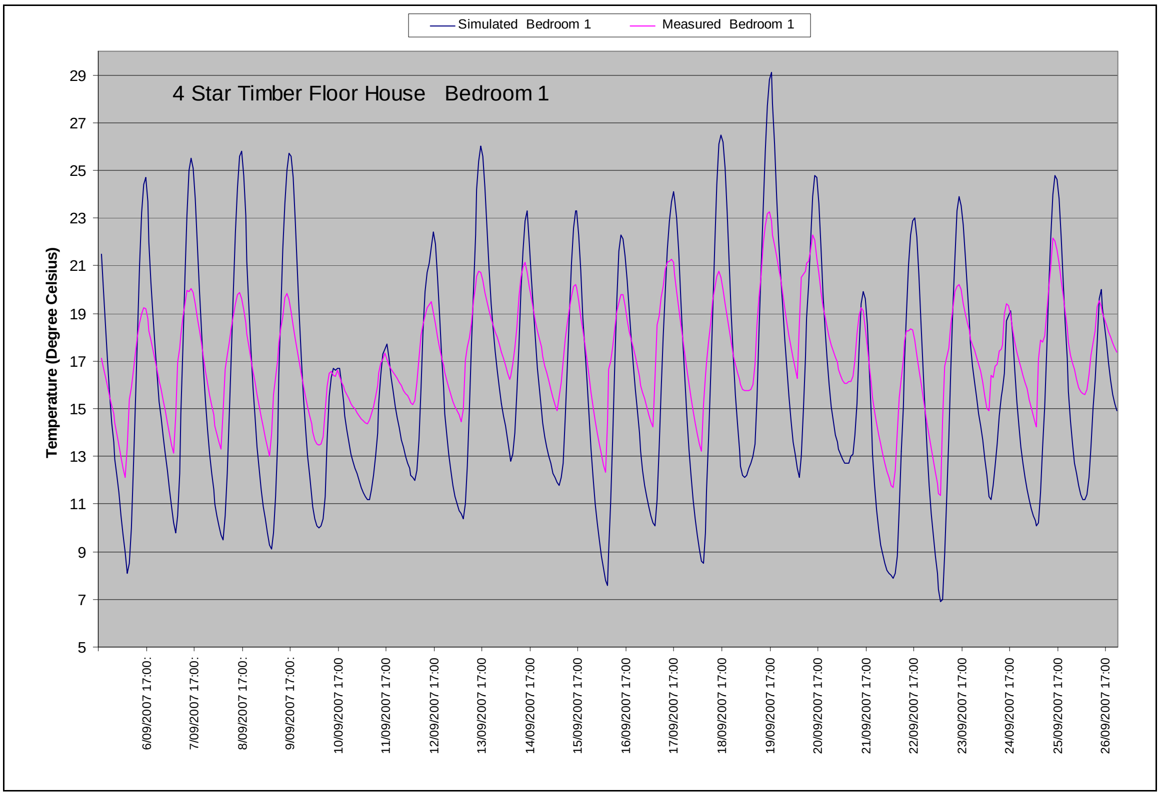


Figure 8.31: Simulated and measured temperatures in bedroom 1 of the 4-star timber floor house

The simulated temperature range of 6.9ºC to 29.1ºC is larger than the measured range of 11.4ºC to 23.4ºC. Simulated maximum temperatures are mostly higher and minimum temperatures are constantly lower, than measured values. Simulated maximum temperatures are close to measured values on only 4 days. Table 8.17 shows a summary of temperature comparison for bedroom 1.

Table 8.17: Comparison of measured and simulated temperatures in bedroom 1 of the 4-star timber floor house

Description	Simulated Temperatures (ºC)	Measured Temperatures (ºC)	Measured – Simulated Temperatures (Residuals) (ºC) *
Temperature range	6.9-29.1	11.4-23.4	
Average temperature	16.0	17.1	+ 1.1
Average minimum temperature	10.3	14.0	+ 3.7
Average maximum temperature	23.2	19.9	- 3.3

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

The average simulated minimum temperature is 3.7ºC lower and the average maximum temperature 3.3ºC higher compared to the measured values. Figure 8.32 shows the daily maximum and minimum temperatures for bedroom 1 of the 4-star timber floor house.

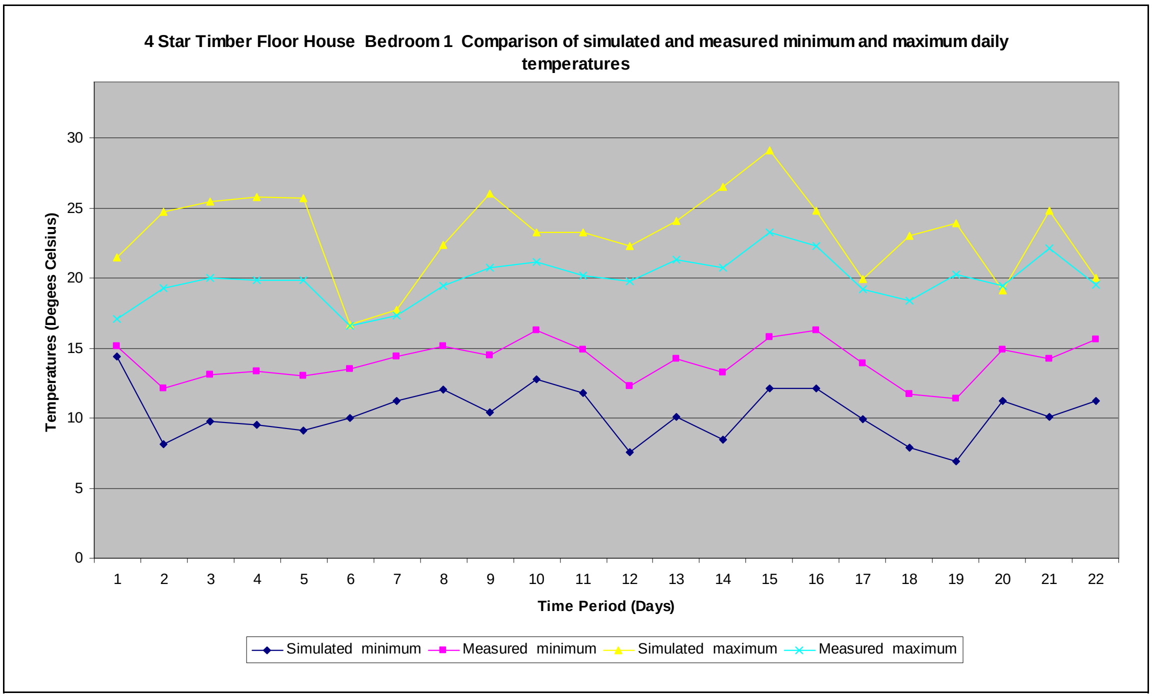


Figure 8.32: Comparison of simulated and measured maximum and minimum daily temperatures in bedroom 1 of the 4-star timber floor house

Average minimum temperatures are, (except on Day 1), 3.6ºC to 4.0ºC lower, compared to the measured values. On Day 1, the simulated temperature is only 0.7ºC lower. Simulated daily average maximum temperatures are in all cases, (except for Day 6) higher with large differences of 5.3ºC to 5.7ºC experienced on numerous days. On Day 6, simulated and measured average maximum temperatures have the same value.

c) Hallway

Figure 8.33 illustrates the simulated and measured temperature profiles for the hallway of the 4-star timber floor house.

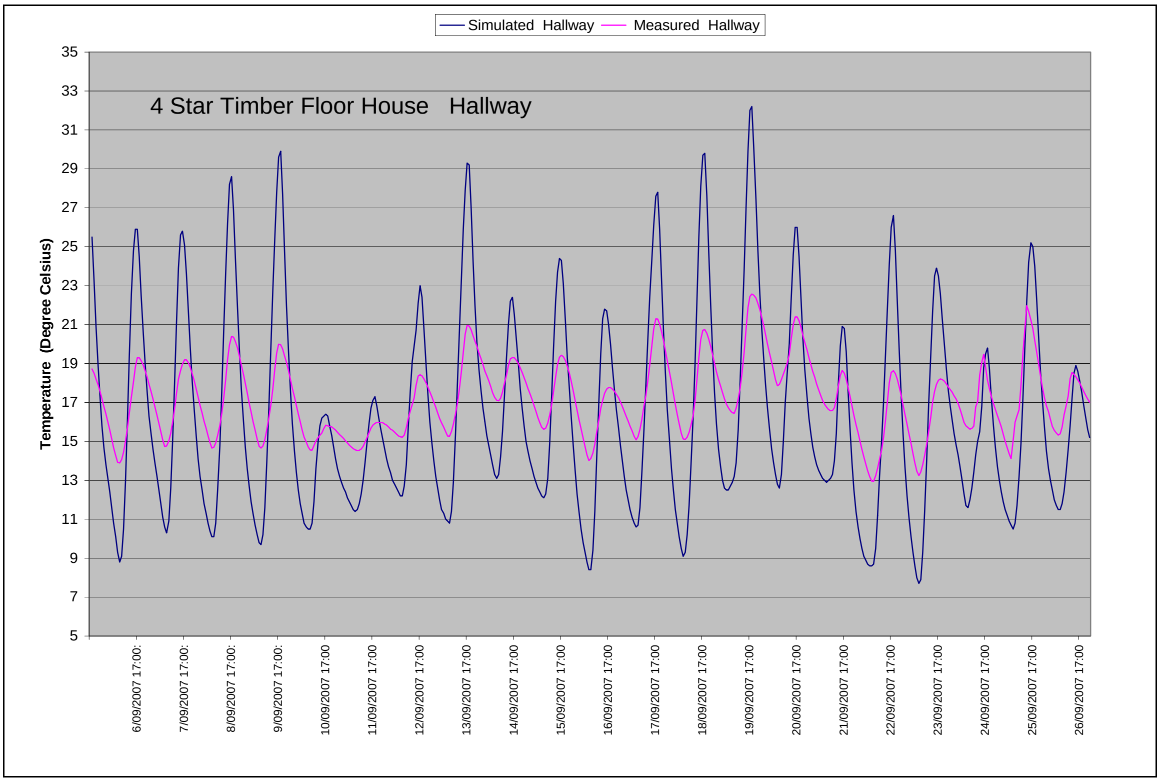


Figure 8.33: Comparison of simulated and measured temperatures in the hallway of the 4-star timber floor house

While temperature profiles are reasonably similar, showing similar trends and swings, simulated maximum temperatures are considerably higher, and minimum temperatures significantly lower, than the measured temperatures. Table 8.18 presents a summary of temperature comparisons for the simulated and measured values.

Table 8.18: Comparison of measured and simulated temperatures in the hallway of the 4-star timber floor house

Description	Simulated Temperatures (ºC)	Measured Temperatures (ºC)	Measured – Simulated Temperatures (Residuals) (ºC) *
Temperature range	8.6-32.2	13.9-22.6	
Average temperature	16.5	17.2	+ 0.7
Average minimum temperature	10.9	15.1	+ 4.2
Average maximum temperature	24.6	19.5	- 5.1

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

The simulated temperatures range from 8.6ºC to 32.2ºC is considerably larger than the measured temperature range of 13.9ºC to 22.6ºC. The average simulated minimum temperature is 4.2ºC lower and the average simulated maximum temperature 5.1ºC higher, than the measured values.

Figure 8.34 shows the daily maximum and minimum temperatures for the hallway of the 4-star timber floor house.

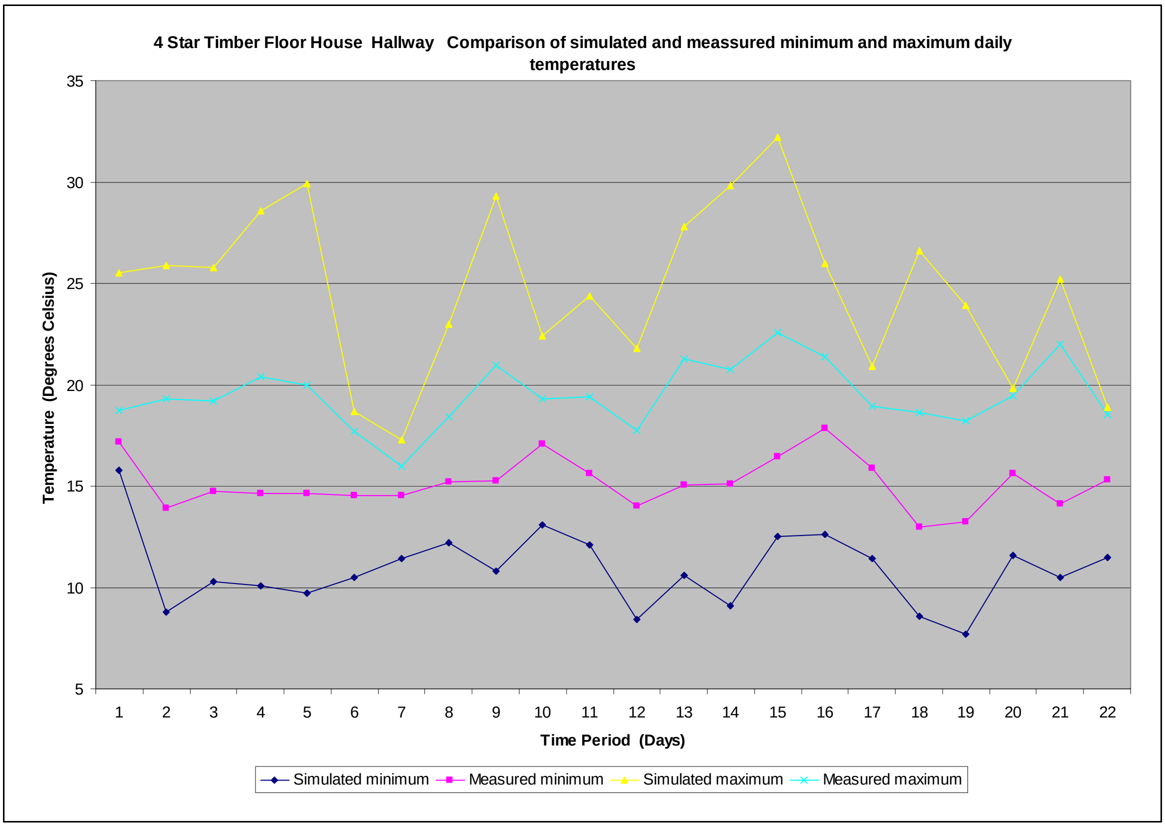


Figure 8.34: Comparison of simulated and measured daily maximum and minimum temperatures in the hallway of the 4-star timber floor house

Simulated minimum temperatures are always 3ºC to 4.6ºC lower, except on Day 1, when the simulated temperature is only 1.4ºC lower. Simulated maximum temperatures are always higher, with the largest temperature differences of 9.6ºC and 10ºC on Days 5 and 15.

d) Roof Space

Figure 8.35 shows the profile of simulated and measured temperatures' comparison in the roof space of the 4-star timber floor house.

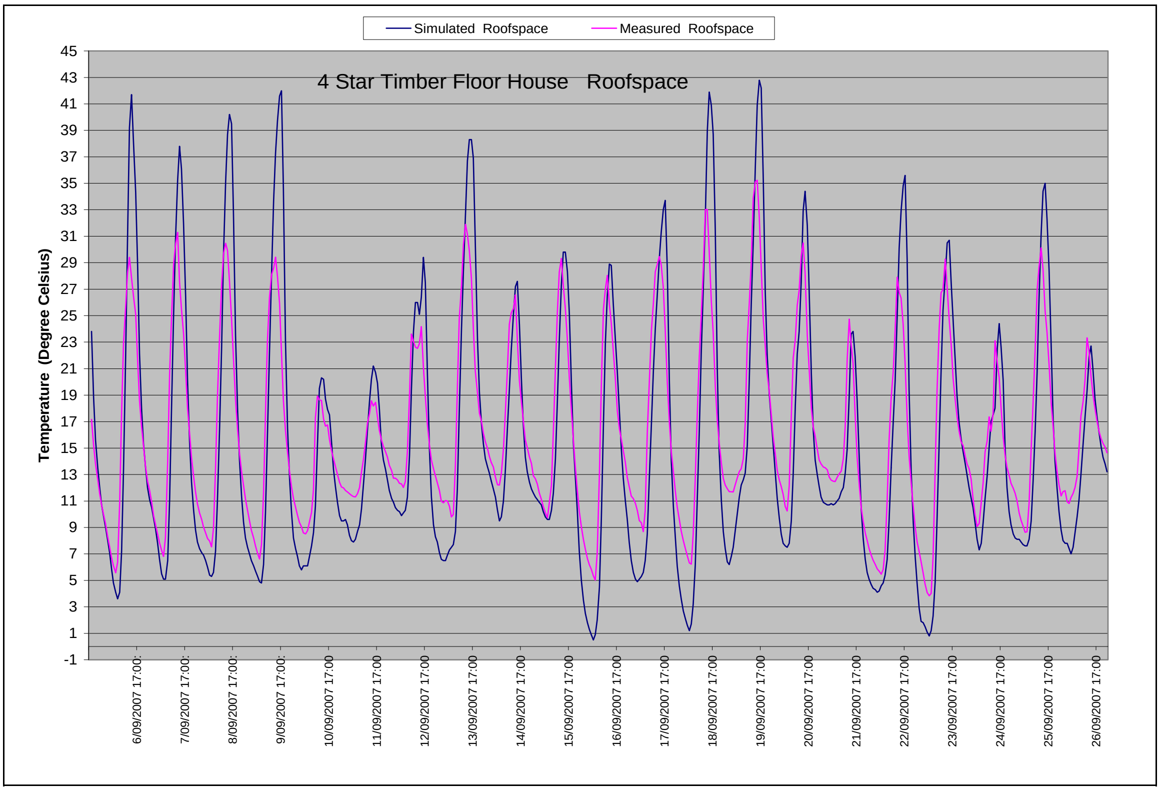


Figure 8.35: Comparison of simulated and measured temperatures in the roof space of the 4-star timber floor house

While temperature profiles are reasonably similar, simulated temperatures are constantly higher, (and lower) than the measured temperatures. Table 8.19 provides a summary of temperature comparisons for the roof space.

Table 8.19: Comparison of measured and simulated temperatures in the roof space of the 4-star timber floor house

Description	Simulated Temperatures (ºC)	Measured Temperatures Sensor (ºC)	Measured – Simulated Temperatures (Residuals) (ºC) *
Temperature range	0.5-41.7	3.8-35.2	
Average temperature	15.4	16.1	+ 0.7
Average minimum temperature	5.7	8.5	+ 2.8
Average maximum temperature	32.1	27.4	- 4.7

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

The simulated average temperature difference is 0.7ºC lower than the measured average temperature. However, larger temperature differences are recorded for the average minimum and maximum temperatures, where the simulated average minimum temperature is 2.8ºC lower and the simulated average maximum temperature is 4.7ºC higher, compared to measured values. Table 8.36 compares the daily maximum and minimum temperatures for the roof space.

Figure 8.36: Comparison of simulated and measured daily maximum and minimum temperatures in the roof space of the 4-star timber floor house

Simulated minimum temperatures are 1ºC to 5ºC lower, except on Day 1, when minimum simulated and measured temperatures have the same value. Maximum simulated temperatures are higher on most days, except for 2 days, when measured temperatures are 0.7ºC and 0.9ºC higher. Maximum simulated temperature is 12.6ºC higher on day 5, 12.3ºC higher on day 2 and 8.8ºC higher on Day14.

e) Subfloor

Figure 8.37 illustrates the temperature profiles' comparison for the subfloor of the 4-star timber floor house.

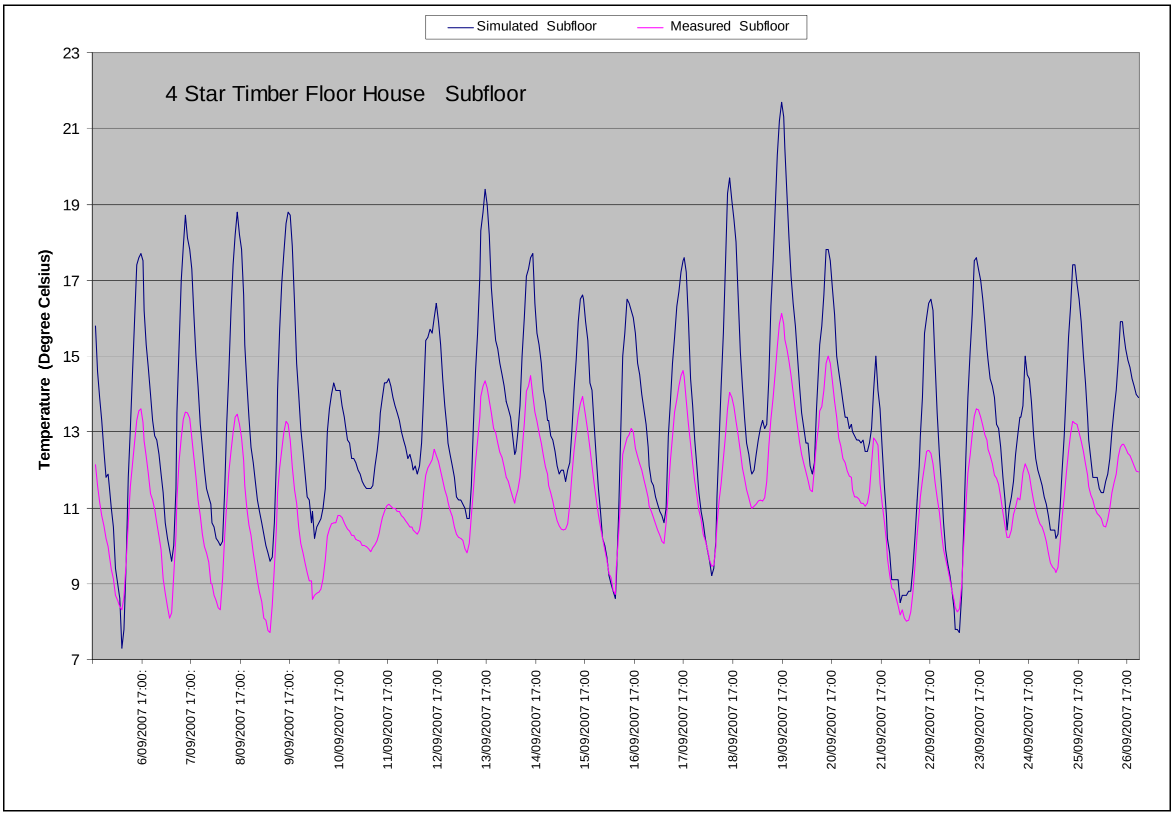


Figure 8.37: Comparison of simulated and measured temperatures in the subfloor of the 4-star timber floor house

While minimum simulated temperatures are reasonably similar to the measured temperatures, maximum simulated temperatures are always significantly higher. This is especially the case on Day 14 (19 September 2007), when the maximum simulated temperature was 22ºC, while the maximum measured temperature showed only 16ºC. Table 8.20 presents a summary of temperature comparisons for the subfloor.

Table 8.20: Comparison of measured and simulated temperatures in the subfloor of the 4-star timber floor house

Description	Simulated Temperatures (ºC)	Measured Temperatures Sensor (ºC)	Measured – Simulated Temperatures (Residuals) (ºC) *
Temperature range	7.3-21.7	7.7-16.1	
Average temperature	13.5	11.3	- 2.2
Average minimum temperature	10.3	9.5	- 0.8
Average maximum temperature	17.2	13.3	- 3.9

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

The simulated temperatures of the subfloor ranges from 7.3ºC to 21.7ºC while the measured temperature ranges from 7.7ºC to 16.1ºC. The average simulated temperature is 2.2ºC higher.

Compared to the measured values the average simulated minimum temperature is 0.8ºC higher, and the average simulated maximum temperature is 3.9ºC higher.

Figure 8.38 shows the simulated and measured daily maximum and minimum temperatures for the subfloor.

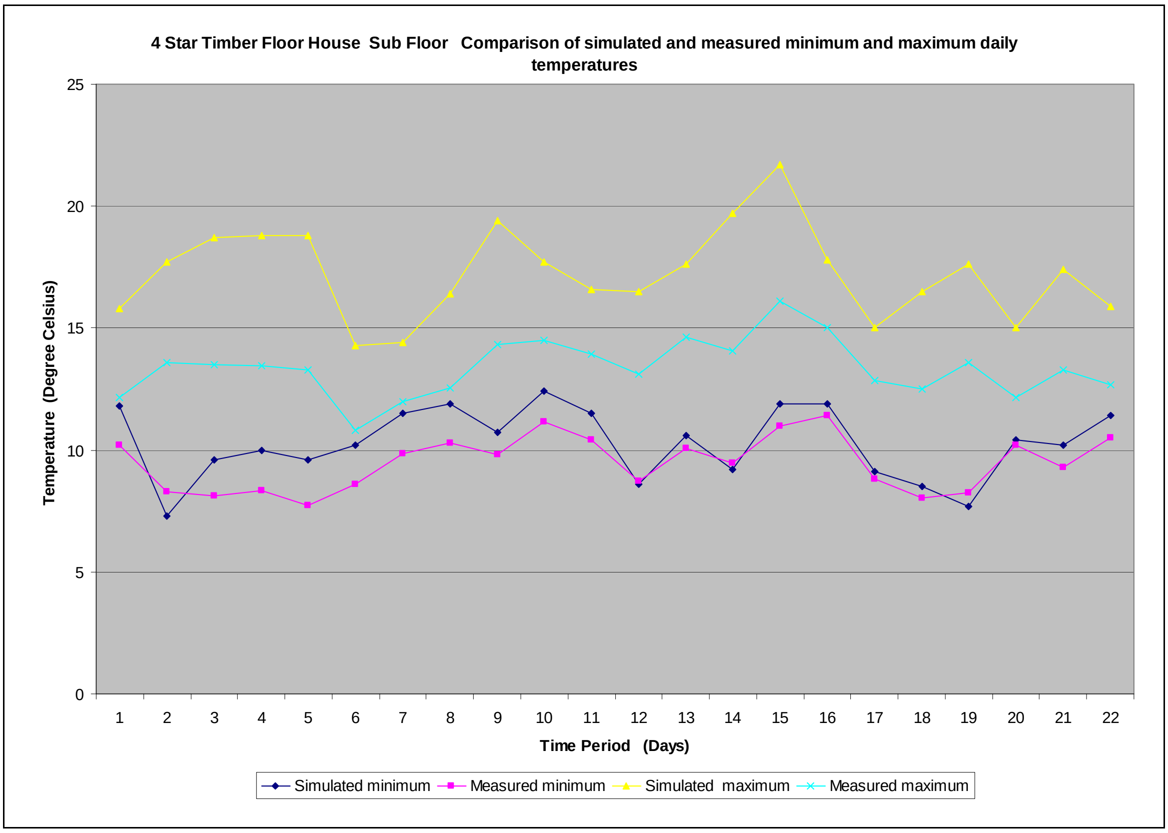


Figure 8.38: Comparison of simulated and measured daily maximum and minimum temperatures in the subfloor of the 4-star timber floor house

While in most house zones minimum simulated temperatures are generally lower, this is not the case in the subfloor of both timber houses. Here, minimum simulated temperatures are mostly between 0.3ºC and 1.7ºC higher, except on Days 1, 2, 12 and 19, where measured temperatures are slightly higher. On Day 1, the measured minimum temperature is 2.7ºC higher. Maximum simulated temperatures are always notably higher, with the maximum temperature difference of 5.6ºC recorded on Day 15.

f) House Zone Temperature Comparison

Table 8.21 represents a summary of temperature comparisons for the 4-star timber floor house.

Table 8.21: Comparison of ranges, average minimum and average maximum measured and simulated temperatures of the 4-star timber floor house

	Type of Measured Temperature					
Zone	Average Minimum Simulated Temperature (ºC)	Average Minimum Measured Temperature (ºC)	Difference (Minimum Measured – Minimum Simulated Temperature) (ºC) *	Average Maximum Simulated Temperature (ºC)	Average Maximum Measured Temperature (ºC)	Difference (Maximum Measured – Maximum Simulated Temperature (C) *
Living Room	9.6	13.4	+ 3.8	29.9	26.7	-3.2
Bedroom 1	10.3	14.0	+ 3.7	23.2	19.0	- 3.3
Hallway	10.9	15.1	+ 4.2	24.6	19.5	- 5.1
Roof Space	5.7	8.5	+ 2.8	32.1	27.4	- 4.7
Sub Floor	10.3	9.5	- 0.8	17.2	13.3	- 3.9

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

With the exception of the subfloor, AccuRate always under-predicted the minimum average temperature and constantly over-predicted the average maximum temperatures. Simulated temperatures are most similar in the subfloor, where the simulated average minimum temperature is only 0.8ºC higher than the measured value. Average minimum temperatures between simulated and measured are dissimilar in the hallway, where the minimum average temperature is 4.2ºC lower and the average maximum temperature is 5.1ºC higher compared to the measured temperatures. The average simulated minimum temperature in the subfloor indicates the only opposing trend, where the simulated temperatures are actually significantly higher than the measured value. For all other zones, the simulated average minimum temperatures are always lower.

8.3.4. Comparison of Temperatures in various Zones of the Test Houses

In this section, temperature ranges and average minimum and maximum temperatures of simulated and measured values of the three test houses are compared with each other. The following house zones of the houses are compared, namely:

- Living room;
- Bedroom 1;
- Hallway;
- Roof space;
- Subfloor of the 4 and 5-star timber floor houses.

Table 8.22 shows the summary of temperature comparisons for: the living room, bedroom 1, hallway, roof space and subfloor of the slab floor house, and the 4-star and 5-star timber floor houses.

Table 8.22: Comparison of measured and simulated temperatures in various zones of the three test houses

House Type	Simulated Temp .Range (ºC)	Measured Temp. Range (ºC)	Simulated Average Minimum Temp (ºC)	Measured Average Minimum Temp (ºC)	Measured Minimum - Simulated Minimum Temp (ºC) *	Simulated Average Maximum Temp (ºC)	Measured Average Maximum Temp (ºC)	Measured Maximum - Simulated Maximum Temp (ºC) *
Slab Living	9.7-35.1	10.5-32.2	12.2	13.0	+0.8	28.7	26.9	-1.8
Slab Bed 1	10.1-23.4	10.6-21.7	12.2	12.3	+0.1	19.7	18.0	-1.7
Slab Hallway	11.7-26.2	14.3-24.1	13.3	15.7	+2.4	21.1	19.7	-1.4
Slab Roof Space	0.4-42.4	4.9-32.6	5.5	8.5	+3.0	31.7	27.2	-4.5
5-Star Living	5.2-39.1	9.3-33.6	9.0	12.6	+3.6	28.2	27.3	-0.9
5-Star Bed 1	6.0-29.8	10.0-21.5	9.6	12.7	+3.1	23.4	18.3	-5.5
5-Star Hallway	6.8-31.3	11.5-21.0	10.0	14.0	+4.0	23.6	18.5	-5.1
5-Star Roof Space	0.5-43.3	3.7-35.9	5.7	8.7	+3.0	32.7	28.1	-4.6
5-Star Sub Floor	7.2-21.4	8.3-16.9	10.1	10.0	-0.1	16.9	14.0	-2.9
4-Star Living	5.9-41.1	10.3-33.0	9.6	13.4	+3.8	29.9	26.7	-3.2
4-Star Bed 1	6.9-29.1	11.4-23.4	10.3	14.0	+3.7	23.2	19.9	-3.3
4-Star Hallway	8.6-32.2	13.9-22.6	10.9	15.1	+4.2	24.6	19.5	-5.1
4-Star Roof Space	0.5-41.7	3.8-35.2	5.7	8.5	+2.8	32.1	27.4	-4.7
4-Star Sub Floor	7.3-21.7	7.7-16.1	10.3	9.5	-0.8	17.2	13.3	-3.9

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

a) Living Rooms

In the living rooms of the three houses, AccuRate's simulated temperature ranges are always wider than the measured values, recording lower minimum and higher maximum temperatures. Simulated temperature ranges are much closer to measured values in the slab floor house than in the 4 and 5-star timber floor houses The lowest average minimum temperature difference between simulated and measured values is recorded in the slab floor house (simulated 0.8ºC cooler) and the highest average minimum temperature difference is documented in the 4-star timber floor house (simulated 3.8ºC cooler). The lowest average maximum temperature difference occurs in the 5-star timber floor house, (simulated 0.9ºC warmer) and the largest average maximum temperature difference in the 4-star timber floor house (simulated 3.2ºC warmer).

b) Bedroom 1

Simulated temperature ranges are always wider than measured values, showing lower minimum and higher maximum temperatures. Simulated temperature ranges are closer to measured temperature values in the slab floor than to the 4 and 5-star timber floor houses. The lowest average minimum and maximum temperature difference between simulated and measured values occurs in the slab floor house where the simulated average minimum temperature was 0.1ºC lower and the simulated average maximum temperature 1.7ºC higher than measured values. The highest average maximum temperature difference is recorded in the 5-star timber floor house, where the simulated average maximum temperature is 5.5ºC higher than the measured temperature values.

c) Hallway

Simulated temperature ranges in the hallway are wider than measured temperature ranges, displaying lower minimum and higher maximum temperatures. Simulated temperature ranges were closer to measured temperature values in the slab floor house than in the 4 and 5-star timber floor houses. The lowest average minimum and maximum temperature difference between simulated and measured values occurs in the slab floor house, where the simulated minimum temperature is 2.4ºC lower and the simulated average maximum temperature is 1.4ºC higher than the measured temperature. Significantly higher temperature differences between average minimum and maximum simulated and measured temperatures are recorded in the 4 and 5-star timber floor houses than in the slab floor house.

d) Roof space

Temperature ranges and differences of average maximum and minimum temperatures are different for all three houses. Simulated temperature ranges in the roof space are significantly wider than measured temperature ranges, showing lower minimum and higher maximum temperatures The smallest average minimum temperature difference occurs in the 4-star timber floor house (simulated 2.8ºC lower) and the largest minimum temperature difference in the slab floor house and the 5-star timber floor house (simulated 3.0ºC lower). The smallest average maximum temperature difference is documented in the slab floor house (simulated 4.7ºC higher) and the largest average maximum temperature difference in the 4-star timber floor house (simulated 4.7ºC higher).

e) Subfloor

Simulated temperature ranges in the subfloor are also wider than measured temperature values. The 5-star timber floor house records the smallest average minimum temperature difference (simulated 0.1ºC higher), and also records the lowest average maximum temperature (simulated 2.9ºC higher) compared to the 4-star timber floor house. The 4-star timber floor house records 0.8ºC higher simulated temperatures for the average minimum temperature and 3.9ºC higher temperatures for the average maximum temperature.

While simulations constantly under-predicted temperatures in all zones of the house, simulations for the 5-star and the 4-star houses constantly over-predicted temperatures in the subfloor. The over-predictions in the subfloor are less for the minimum temperatures than for the maximum temperatures.

f) Summary

1. Simulated temperature profiles fundamentally match with the measured profiles, but simulated hourly temperature levels do not match measured levels and are at times quite dissimilar.

2. Simulated temperature ranges in all zones are larger than the measured temperature ranges, in all zones of the houses, recording lower minimum and higher maximum temperatures. This is particularly the case in the roof space of all the houses, where the software over-predicted temperatures by: up to 9.9ºC in the slab floor house, by up to 7.4ºC in the 5-star timber floor house and by up to 6.5ºC in the 4-star timber floor house.

3. Simulated temperature ranges are closer to measured values in the living room, bedroom 1, hallway and roof space of the slab floor house, than in the 4 and 5-star timber floor houses;

4. Simulated average minimum temperatures are, with the exception of the subfloor, always lower than measured temperatures in all zones of the houses;

5. Simulated average maximum temperatures are always higher than the measured values for all zones of the houses;

6. The smallest differences between measured and simulated average minimum temperatures are recorded in the slab floor house, where simulated temperatures are

always lower. The smallest difference between measured and simulated average maximum temperatures are, with the exception of the living room of the 5-star timber floor house, recorded in the slab floor house (simulated temperatures are always higher).

7. Simulated temperatures are closest to measured values in bedroom 1 of the slab floor house, where the simulated average minimum temperature is 0.1ºC lower and the simulated average maximum temperature is 1.7ºC higher than the measured value. Simulated temperatures are also very close to measured values in the living room of the slab floor house, where the simulated average minimum temperature was 0.8ºC lower and the simulated average maximum temperature was 1.8ºC higher than measured values.

8. Simulated average minimum temperatures are furthest from measured values in the hallway of all three houses. Simulated average maximum temperatures are furthest from measured temperatures in bedroom 1 of the 5-star timber floor house and in the hallway of all three houses. The greatest difference between simulated and measured average maximum temperature of 5.5ºC is recorded in bedroom 1 of the 5-star timber floor house.

The next section presents the statistical empirical analysis for this research.

8.4. Empirical Validation Statistical Analysis

8.4.1. Introduction

The graphical analysis in the previous section of this chapter provided a general comparison of AccuRate's prediction relative to the measured temperatures. The graphical analysis showed that the simulated temperature values are, at times, very different from the measured values. The purpose of the following statistical analysis is to investigate the following:

- The difference between the simulated temperature values and the measured values;
- The difference between the results of the houses.

Statistical analyses were undertaken to determine the correlations between the simulated and measured data of each zone of the houses and temperatures of the test houses, and then to examine temperature residuals of two major zones, namely the living room and bedroom 1, of each of the houses. The living room is situated at the north-eastern side, having large windows and glazed sliding doors, and receives a significant amount of solar radiation. On the other hand, bedroom 1, situated at the south eastern side of the houses, receives only a very small amount of solar radiation during the monitored period.

The results are discussed according to the following characteristics:

- The correlation between the simulated and measured temperatures: This investigation also compares measured temperature values with the fitted simulated temperatures, and determines the trend in temperature differences between simulated and measured values. The coefficient of determination (r^2) is shown in the scatterplot diagrams of simulated versus measured temperatures and provides information about the goodness-of-fit of a model. It is a statistical measure of how well the regression line approximates the real measured data points (Palmo, Marco & Madson 1997). For example an r^2 of 1.0 indicates that the regression line perfectly fits the data while an r^2 of 0.2 indicates that the data does not fit the regression line. In addition r^2 is the square of the correlation coefficient r between real and predicted values.

- The frequency, distribution and range of residuals: This analysis also provides information on the proportion of time that the software under or over-predicted temperatures during the monitored period;

- The correlation of residuals between two adjacent zones: The temperature residuals (errors) of the two zones are compared. The correlation coefficient (r) is shown on the scatterplot diagrams of residuals between adjacent zones and on the scatterplot diagrams of room residuals and climate parameters. It provides information of the strength of linear relationship between real and predicted values (Agami & Reddy 2006).

- The correlation of the room residual and the climate parameters, namely: external air temperature, global solar radiation, wind speed, and wind direction. This investigation discloses the variation of residuals with climatic variation.

In the latter part of this chapter, the results for the three houses are compared and summarised. The program used for the statistical analysis is Statistica Release 7.

8.4.2. The Slab Floor House

a) Living Room

<u>1) Correlation between Simulated and Measured Temperature for the Living Room</u>

The scatterplot of simulated and measured temperatures for the living room is shown in Figure 8.39. Temperatures were taken for each hour for both, the measured and simulated temperatures between 5 September 2005 and 26 September 2007. Each point of the scatterplot graph represents a particular measurement of temperature, either measured or simulated. The best fit and perfect fit lines are drawn for comparison, and the coefficient of determination (r^2) is indicated at the bottom left hand corner.

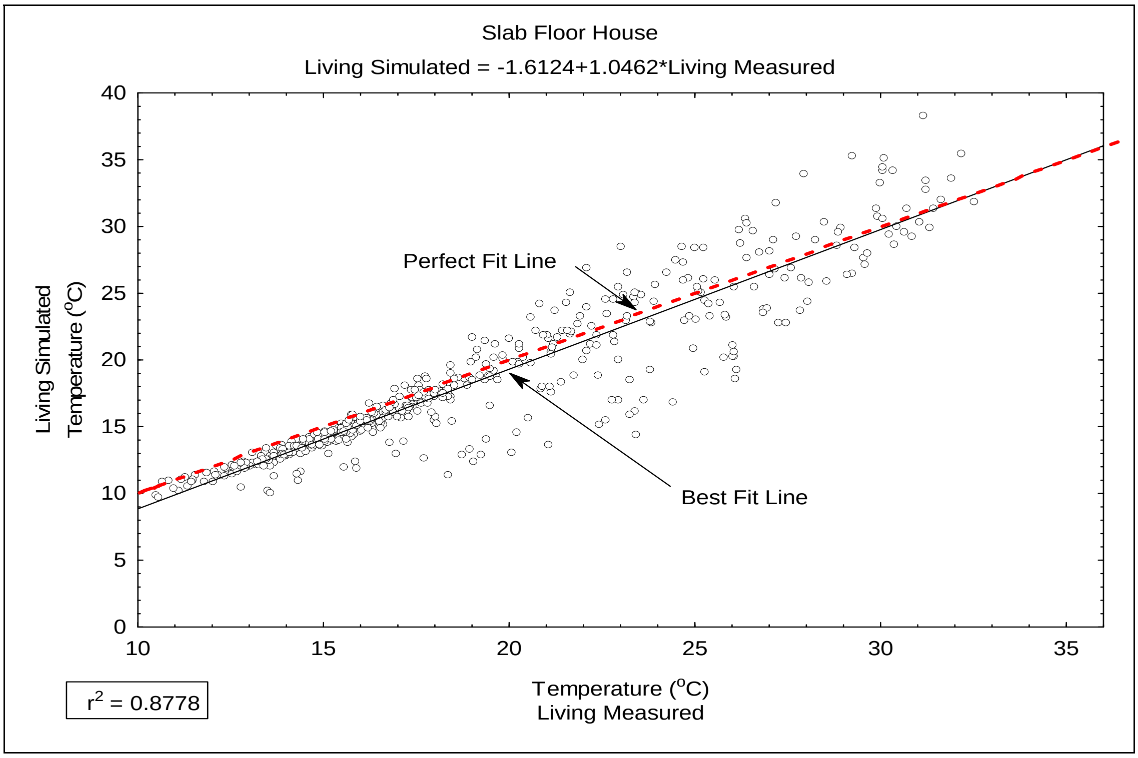


Figure 8.39: Scatterplot of simulated versus measured temperatures for the living room of the slab floor house

For the living room, measured temperature and simulated temperatures have a very good linear correlation, with an r^2 value of 0.8778. The data is tightly grouped around the best of-fit-line between measured temperatures of 11ºC to 19ºC, whereas above 19ºC the data becomes more scattered. This suggests that the software predicted more consistently between 11ºC and 19ºC, compared to predictions over 19ºC. Comparing the perfect fit line and the line of best fit, it can be seen that, whereas the software under-predicted at lower temperatures, the two lines eventually converge at the higher temperature of 34.9ºC. It is also interesting to note, that the software's under-prediction increased as the temperature decreased, as shown in Table 8.23. This table shows the best-fitted simulated temperatures at a measured temperature of 10ºC to 30ºC.

Table 8.23: Fitted values of simulated temperature at various measured temperatures for the living room of the slab floor house

Measured Temperature (ºC)	Simulated Temperature (ºC)	Residual Temperature (ºC) *
10	8.85	+1.15º
14	13.03	+0.97º
18	17.22	+0.78º
22	21.40	+0.60º
26	25.59	+0.41º
30	29.74	+0.23º

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Table 8.23 confirms that the software under-predicted temperatures between the measured range of 10ºC to 30ºC by 0.23ºC to 1.15ºC, and that prediction were closer to measured values at higher temperatures.

2) Distribution of Temperature Residuals of the Living Room

The residual histogram for the living room of the slab house is shown in Figure 8.40. The figure also indicates that residuals are normally distributed.

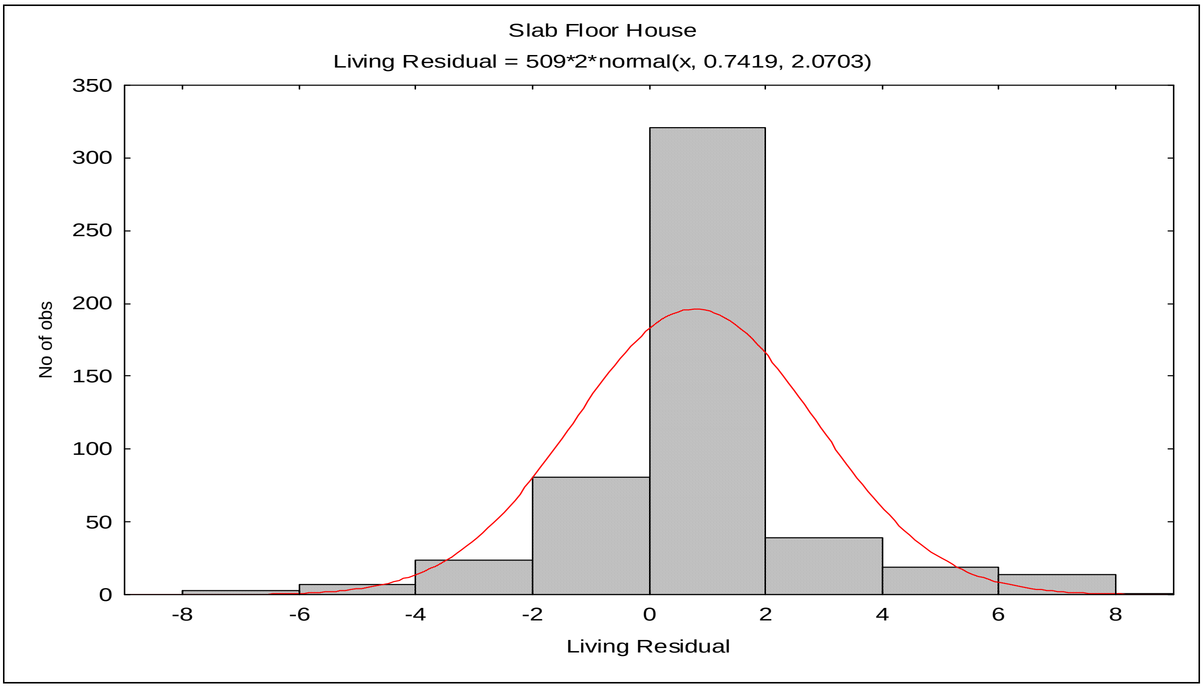


Figure 8.40: Distribution of residuals for the living room of the slab floor house

The majority of individual residual values fall between 0ºC to 2ºC, corresponding to an under-prediction of up to 2ºC for 325 hours or 63.9% time. There were about 80 hours (or 15.7% of time) where the simulation over-predicted temperatures by 0ºC-2ºC.

The software under-predicted the living room temperature 77% of the time and over-predicted temperatures 23% of the time, during the monitoring period.

3) Analysis of Temperature Residuals of Adjoining Zones

Figures 8.41 to 8.43 show the scatterplot diagrams of residuals of the living room and the adjoining zones, namely: bedroom 2, the hallway and the roof space. The best fit line and perfect fit line are also shown in each scatterplot diagram.

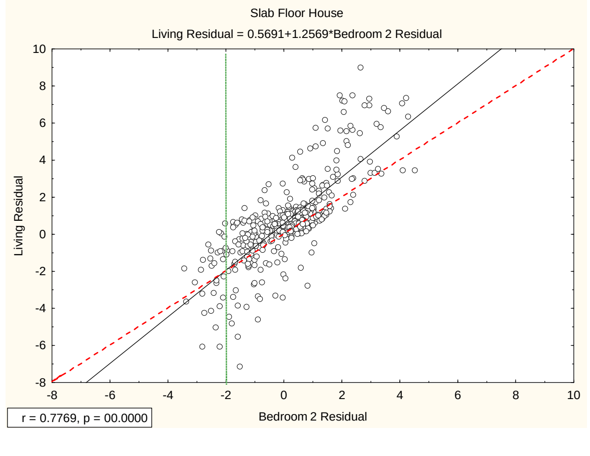


Figure 8.41: Scatterplot of living room and bedroom 2 residuals of the slab floor house

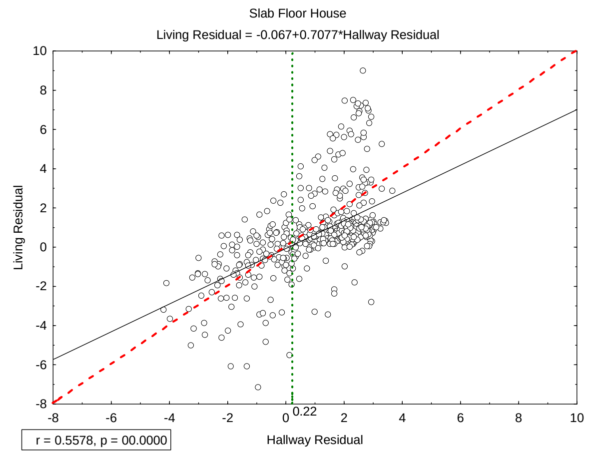


Figure 8.42: Scatterplot of living room and hallway residuals of the slab floor house

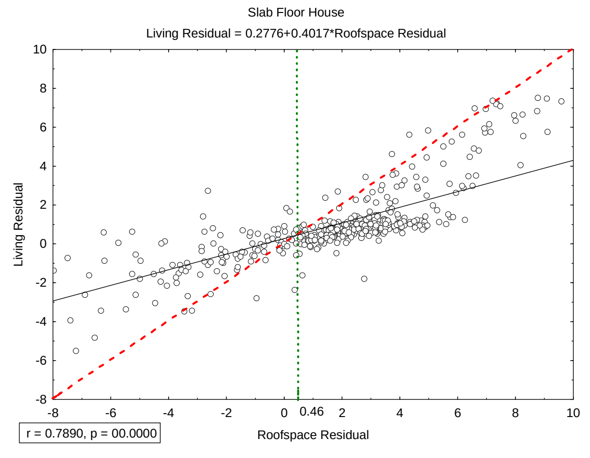


Figure 8.43: Scatterplot of living room and roof space residuals of the slab floor house

Figures 8.41 to 8.47 indicate moderate (r=0.5578) to high (r=0.7769 and 0.7890) correlations between the residuals of the living room temperature and the residuals of its adjoining zones. This can be explained by the thermal connection between adjacent zones in the physical model. Table 8.24 shows a comparison of the fitted residuals of bedroom 2, hallway and the roof space, at selected temperature values of living room residuals.

Table 8.24: Fitted values of bedroom 2, hallway and roof space residuals at selected living room residuals in the slab floor house

Residuals (ºC) *			
Living Room	Bedroom 2	Hallway	Roof Space
-6	-5.23	-8.38	-15.63
-4	-3.64	-5.56	-10.65
-2	-2.04	-2.73	-5.67
0	-0.45	+0.09	-0.69
+2	+1.14	+2.92	+4.29
+4	+2.73	+5.75	+9.27
+6	+4.23	+8.57	+14.25

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Table 8.24 shows similar trends in the magnitude and direction of residuals for all zones. The magnitude of over and under-prediction in the hallway and the roof space is always greater than in the living room. For example, when the software over-predicted temperature in the living room by 6ºC, it over-predicted temperature in the roof space by 15.63ºC, and when the software under-predicted temperature in the living room by 6ºC, it under-predicted temperature in the roof space by 14.25ºC. In contrast, the magnitude of over and under-prediction for bedroom 2 is generally less than for the living room. In all cases, the residuals increase with the amount of under or over-prediction of temperatures.

4) Correlation between Living Room Residuals and Various Climate Parameters

Figures 8.44 to 8.47 show the scatterplots of the living room residuals versus the external climate parameters, namely: the external air temperature, global solar radiation, wind speed and wind direction. All the diagrams show the line of best fit (black continuous line) and the line of zero residuals (red dotted line). A green vertical dotted line shows where the best-of-fit line converges with the line of zero temperature residuals (temperature errors). The correlation coefficient (r) is indicated on the bottom left corner of each diagram.

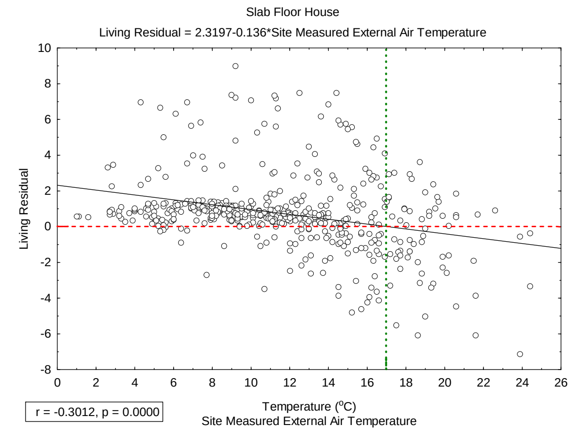


Figure 8.44: Scatterplot of living room residuals and external air temperature of the slab floor house

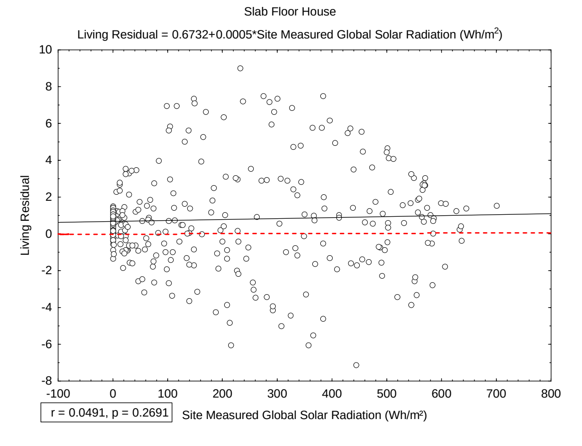


Figure 8.45 Scatterplot of living room residuals and global solar radiation of the slab floor house

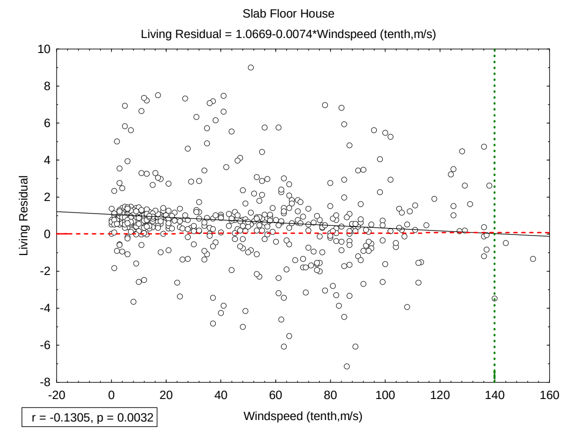


Figure 8.46: Scatterplot of living room residuals and wind speed of the slab floor house

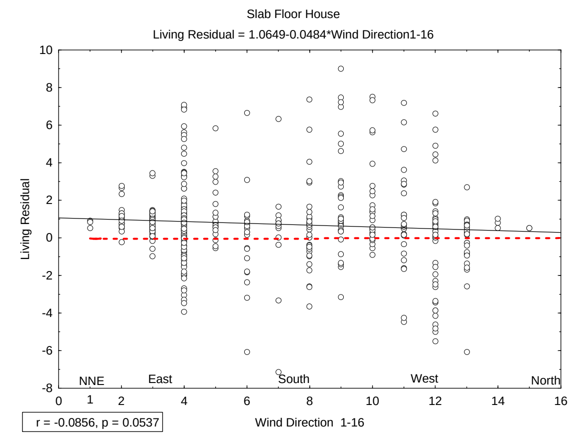


Figure 8.47: Scatterplot of living room residuals and wind direction of the slab floor house

Figure 8.44 shows that the software is generally under-predicting the living room temperatures at lower external temperatures. The magnitude of under-prediction decreases until an external temperature of 17°C, after which the living room temperatures are over-predicted. Table 8.25 shows the fitted living room residuals at various external temperatures.

Table 8.25: Fitted values of living room residuals at selected external temperatures of the slab floor house

External Temperature (ºC)	Slab Floor House Living Room Residuals (ºC) *
2	+2.05
6	+1.50
10	+0.96
14	+0.42
18	-0.13
22	-0.67
26	-1.21

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Table 8.25 shows that at a low external temperature of 2ºC the software under-predicted living room temperature by 2.05ºC, and at higher external temperature of 26ºC the software over-predicted temperature by 1.21ºC. Figures 8.45 to 8.47 show very low r values, indicating that global solar radiation, winds speed and wind direction had no direct linear relationship with the living room residuals.

b) Bedroom 1

<u>1) Correlation of Simulated and Measured Temperature for Bedroom 1 for the Slab Floor House</u>

The scatterplot of simulated and measured temperatures for bedroom 1 is shown in Figure 8.48.

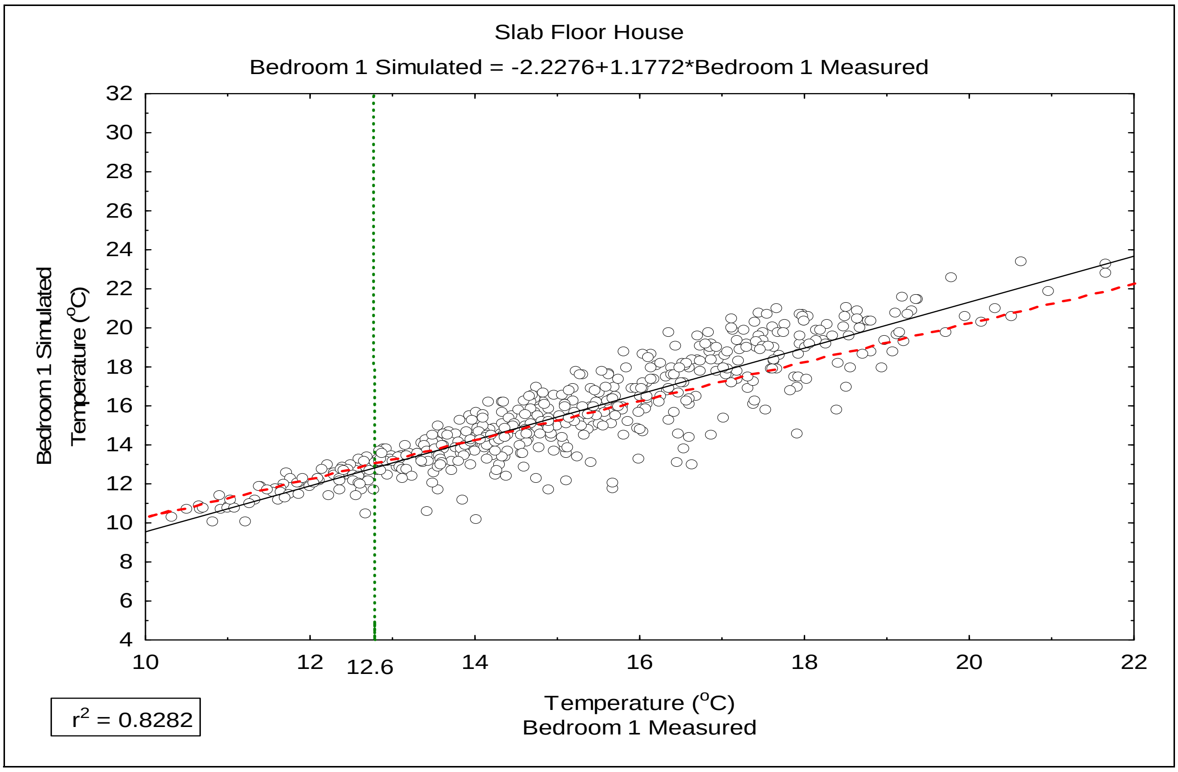


Figure 8.48: Scatterplot of simulated temperature versus measured temperature for bedroom 1 of the slab floor house

The bedroom 1 measured temperature and simulated temperature have a very good linear relation, with an r^2 of 0.8282. The data is concentrated between the measured temperatures of 12ºC and 18ºC. The line of best fit intersects the perfect fit line at 12.6ºC. Consequently simulated temperatures around 12.6ºC were closest to measured values. Below 12.6ºC, the software under-predicted room temperatures, and over 12.6ºC, the software over-predicted room temperatures. Table 8.26 shows the fitted simulated temperatures and the corresponding residual temperatures at various measured temperatures for bedroom 1.

Table 8.26: Fitted values of simulated temperature and corresponding residuals at various measured temperatures for bedroom 1 in the slab floor house

Measured Temperature (ºC)	Simulated Temperature (ºC)	Residual Temperatures (ºC) *
10	9.54	+0.6
12	11.89	+0.1
14	14.25	-0.25
16	16.67	-0.67
18	18.96	-0.96
20	21.32	-1.32

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Table 8.26 shows that the software under-predicted temperatures between the measured temperatures range of 10ºC to 12ºC by 0.6ºC to 0.1ºC, and over-predicted temperatures between the measured temperatures range of 14ºC to 20ºC by 0.25ºC to 1.32ºC, respectively.

2) Distribution of Temperature Residuals for Bedroom 1

The residual histogram of temperature residuals for bedroom 1 of the slab house is shown in Figure 8.49. The figure also indicates that the residuals are normally distributed.

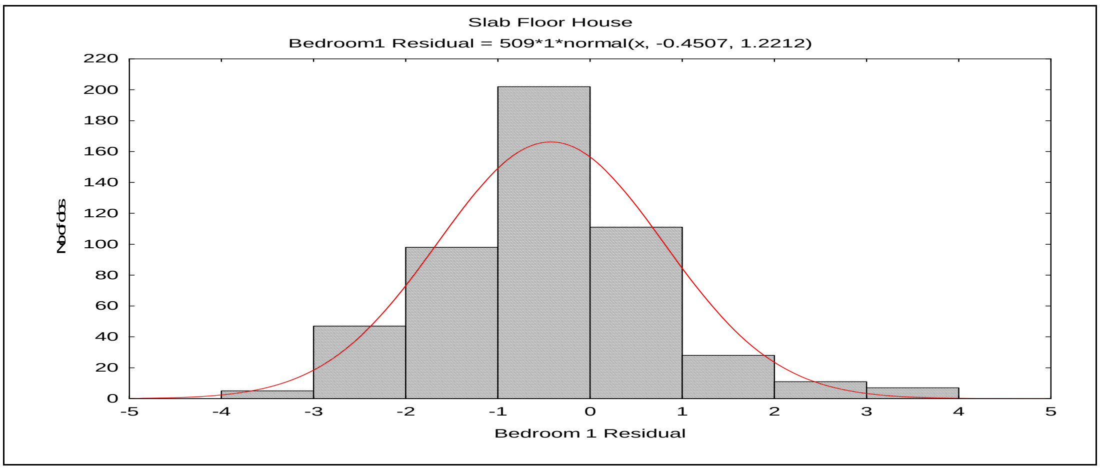


Figure 8.49: Distribution of residuals for bedroom 1 of the slab floor house

Figure 8.49 shows that the software over-predicted temperatures by as much as 1ºC for 200 hrs (or 39.9% of the time). Overall, the software over-predicted temperatures 69% of the time, corresponding to 355 hours. Simulations under-predicted temperatures by up to 1ºC for 115 hrs, or 22.5% of the time. Overall, the software under-predicted temperatures 31% of the time, or corresponding to 154 hours.

3) Analysis of Temperature Residual of Adjoining Zones

Figures 8.50 to 8.52 show the scatterplots of temperature residuals of bedroom 1 versus residuals of the adjoining zones namely: bedroom 2, the hallway, and the roof space.

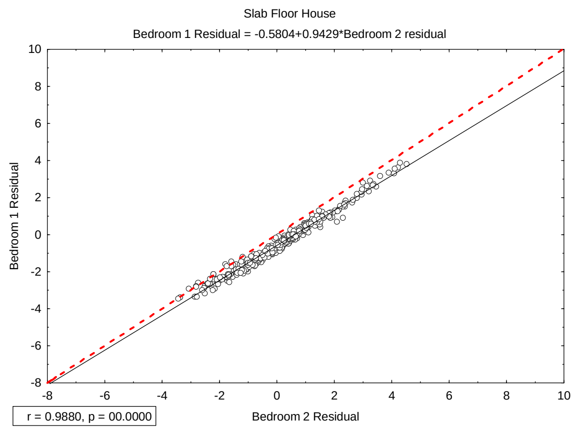


Figure 8.50: Scatterplot of bedroom 1 and bedroom 2 residuals of the slab floor house

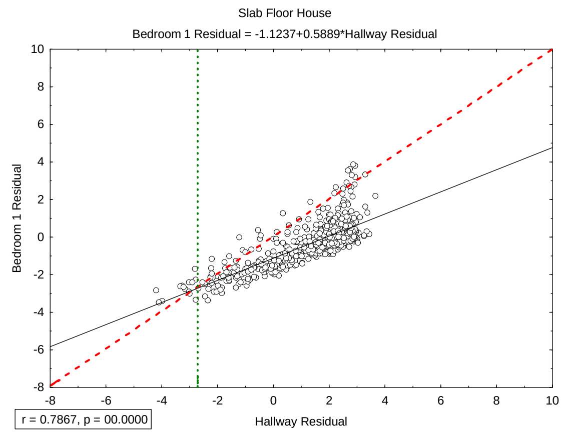


Figure 8.51: Scatterplot of bedroom 1 and hallway residuals of the slab floor house

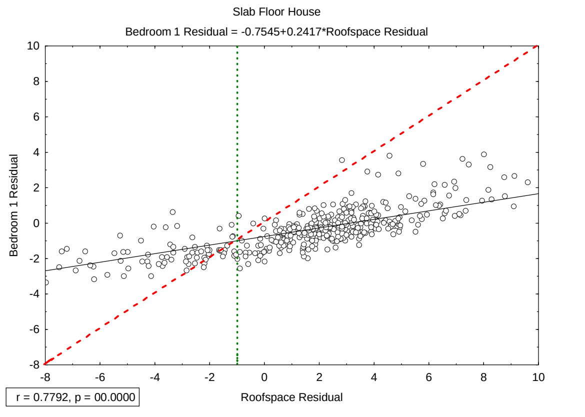


Figure 8.52: Correlation of bedroom 1 and roof space residuals of the slab floor house

Figure 8.50 indicates that the residuals of bedroom 1 and bedroom 2 have a very high correlation coefficient value of 0.9880. Figures 8.51 and 8.52 show that the residuals' comparisons between bedroom 1 hallway and roof space have moderate correlation coefficient at 0.7867 and 0.7792.

Table 8.27 shows the comparison of the fitted temperature residuals for bedroom 2, hallway and roof space at various bedroom 1 temperatures.

Table 8.27: Fitted values of bedroom 2, hallway and roof space residuals at selected bedroom 1 residuals in the slab floor house

Residuals (ºC) *			
Bedroom 1	Bedroom 2	Hallway	Roof Space
-6	-5.75	-8.28	-21.62
-4	-3.63	-4.88	-13.34
-2	-1.51	-1.49	-5.07
0	-0.62	+1.91	+3.21
+2	+2.74	+5.30	+11.48
+4	+4.86	+8.70	+19.76
+6	+6.98	+12.10	+28.03

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Table 8.27 shows that the magnitude and direction of residuals of bedroom 1 and bedroom 2 are similar, whereas the magnitude of residuals of bedroom 1 and the roof space are very dissimilar. For example, when the software over-predicted temperature in bedroom 1 by 6ºC, it over-predicted temperature in the roof space by 21.62ºC and when the software under-predicted temperature in bedroom 1 by 6ºC, it under-predicted temperature in the roof space by 28.03ºC. This suggests that the roof space model requires further investigation. In all cases, the residuals increase with the amount of over and under-prediction. In general, the magnitude of residuals in the hallway is also greater than the residuals in the living room, but not as much as those for the roof space. However, the directions of residuals are similar.

4) Correlation between Bedroom 1 Residuals and Climate Parameters

Figures 8.53 to 8.56 show the scatterplots of bedroom 1 residuals versus the external climate parameters, namely: the external temperature, global solar radiation, wind speed and wind direction.

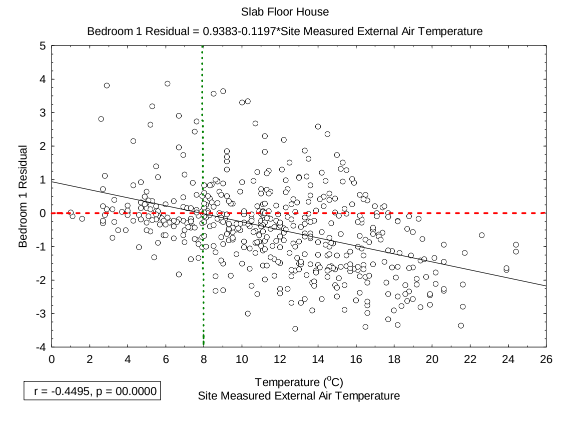


Figure 8.53: Scatterplot of bedroom 1 residuals and external air temperature of the slab floor house

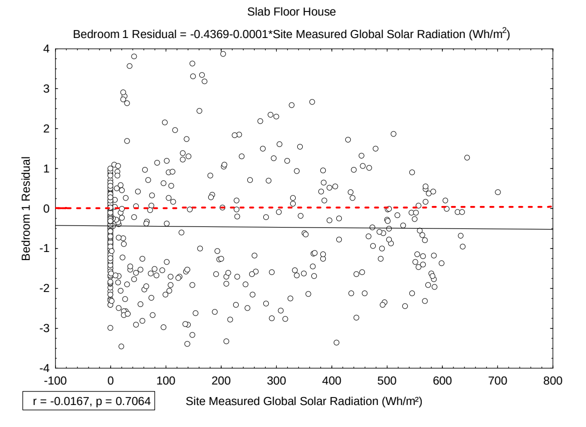


Figure 8.54: Scatterplot of bedroom 1 residuals and global solar radiation of the slab floor house

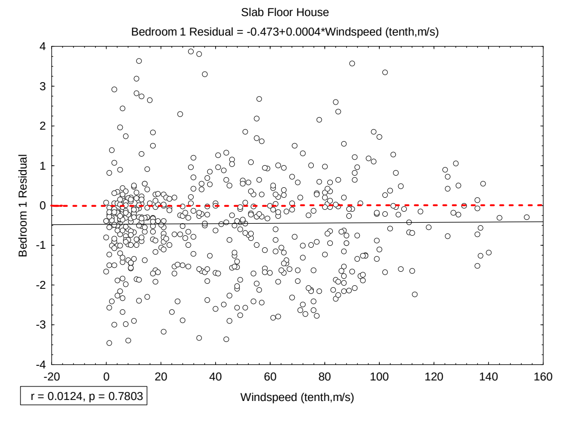


Figure 8.55: Scatterplot of bedroom 1 residuals and wind speed of the slab floor house

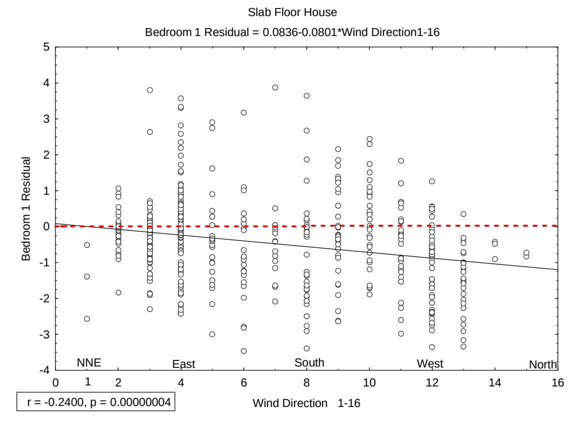


Figure 8.56: Scatterplot of bedroom 1 residuals and wind direction of the slab floor house

Figure 8.53 shows that the software is under-predicting bedroom 1 temperatures at lower external temperatures, the magnitude of which decreases until an external temperature of 8°C, after which the bedroom 1 temperatures are over-predicted. Table 8.28 summarises the fitted values for bedroom 1 residuals at various external temperatures.

Table 8.28: Fitted values of external temperature with bedroom 1 residuals in the slab floor house

External Temperature (ºC)	Slab Floor House Bedroom 1 Residuals (ºC) *
2	+0.69
6	+0.22
10	-0.26
14	-0.74
18	-1.22
22	-1.69
26	-2.17

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Table 8.28 shows that the residuals are smallest at the external temperature of 2ºC, where the software under-predicted temperature by 0.69ºC. The residuals are greatest at the external temperature of 26ºC, where the software over-predicted temperature by 2.17ºC. Figures 8.54 to 8.56 show very low correlations between bedroom 1 residuals and external climate parameters of global solar radiation, wind speed and wind direction. This indicates that global solar radiation, wind speed and wind direction had no direct linear relationship with the living room residuals.

8.4.3. The 5-Star Timber Floor House

a) Living Room

1) Correlation of Simulated and Measured Temperature for the Living Room

Figure 8.57 shows the scatterplot of simulated versus measured temperature for the living room in the 5-star timber floor house.

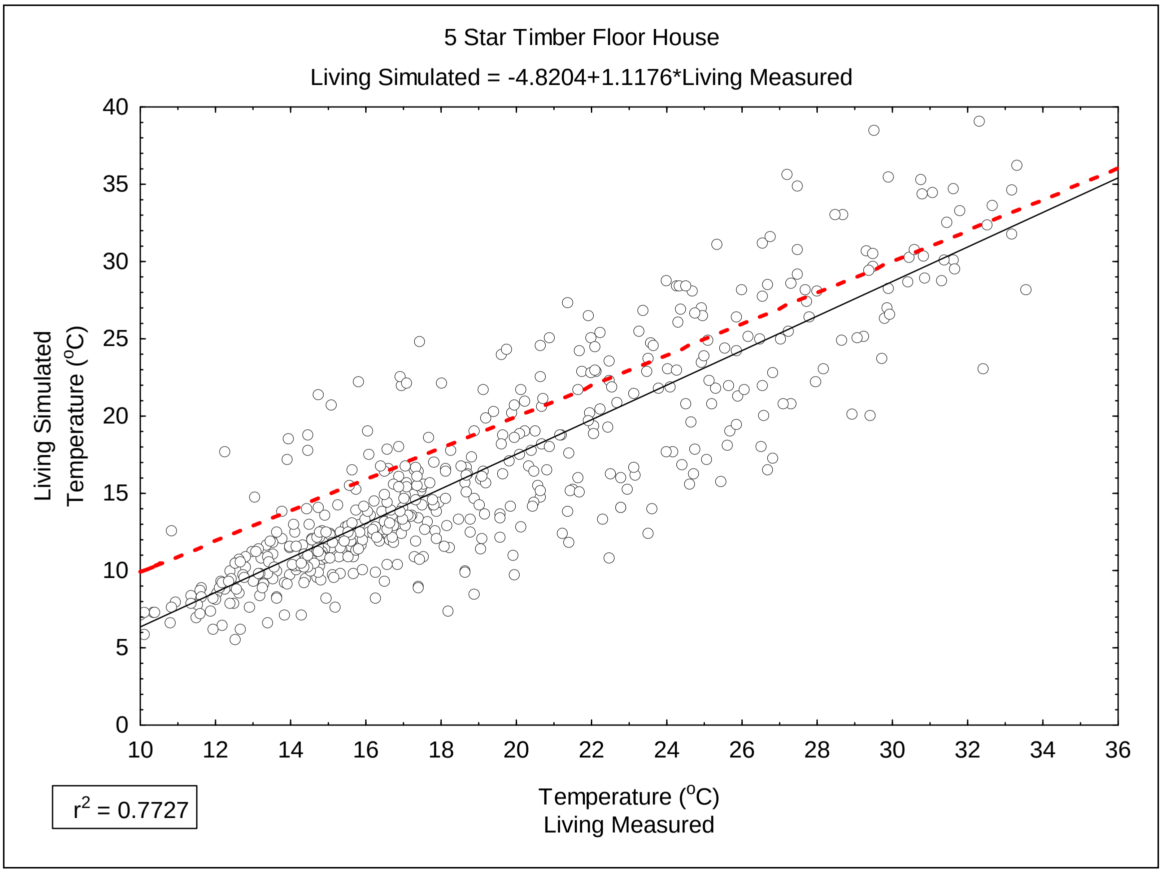


Figure 8.57: Scatterplot of simulated and measured temperature for the living room of the 5-star timber floor house

The linear correlation of living room measured temperature and simulated temperature is good, with an r^2 value of 0.7727. Figure 8.57 shows that data are concentrated around the best-of-fit line between the measured temperature of 12ºC and 18ºC. Above 18ºC the data become more scattered. The best-of-fit line and the perfect fit line converge as temperature increases, indicating that the software's under-predictions decrease as the measured temperatures increase.

Table 8.29 shows the fitted simulated temperatures and the corresponding residuals at measured temperatures from 10ºC to 30ºC. It can be observed that the software continuously under-predicted temperatures throughout the measured temperature range, by 3.64ºC at the measured temperature of 10ºC and by 1.29ºC at the measured temperature of 30ºC.

Table 8.29: Fitted values of simulated temperatures and at various measured temperatures in the living room of the 5-star timber floor house

Measured Temperature (ºC)	Simulated Temperature (ºC)	Residual Temperatures (ºC) *
10	6.36	+3.64
14	10.83	+3.17
18	15.31	+2.69
22	19.77	+2.23
26	24.24	+1.76
30	28.71	+1.29

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

2) Distribution of Temperature Residuals for the Living Room

Figure 8.58 shows the histogram of temperature residuals for the living room. The residuals are normally distributed.

Figure 8.58: Distribution of residuals for the living room of the 5-star timber floor house

The software under-predicted temperatures by 2ºC to 4ºC for 175 hours, or 34.4% of the time. Overall, the software under-predicted temperatures by 60.5% of the time, corresponding to 410 hours. Simulations also over-predicted temperatures by as much as 2ºC for 50 hours (or 9.8% of the time).

3) Analysis of Temperature Residuals of Adjoining Zones

Figures 8.50 to 8.62 show the scatterplot of residuals for the living room versus the adjoining zones, namely: bedroom 2, hallway, roof space and subfloor. The best-of-fit line, perfect-fit line and intersection line of best-of-fit and perfect fit line are shown in each scatterplot.

Figure 8.59: Scatterplot of the living room and bedroom 2 residuals of the 5-star timber floor house

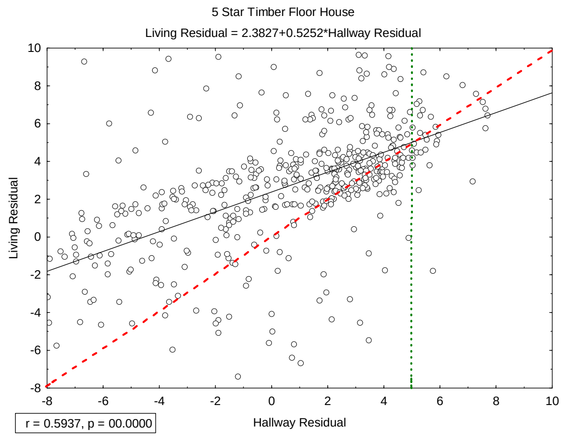


Figure 8.60: Scatterplot of the living room and hallway residuals of the 5-star timber floor house

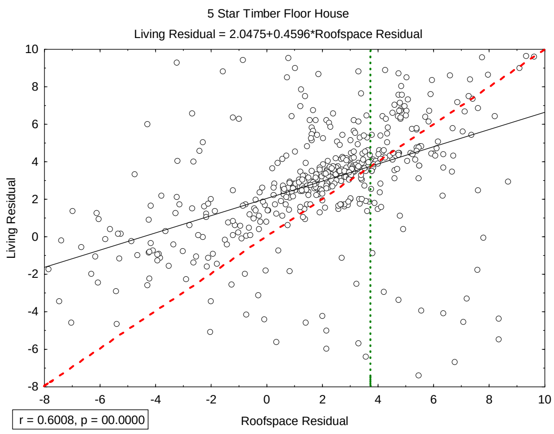


Figure 8.61: Scatterplot of the living room and roof space residuals of the 5-star timber floor house

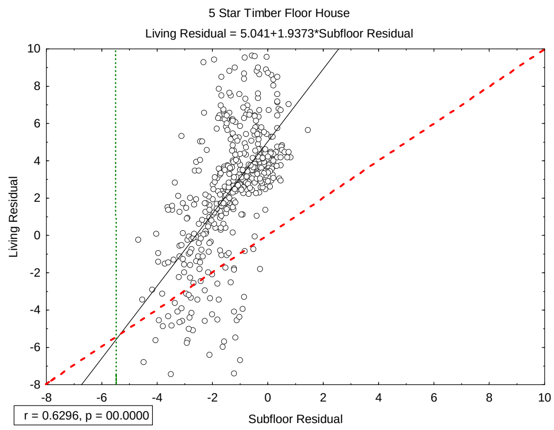


Figure 8.62: Scatterplot of the living room and subfloor residuals of the 5-star timber floor house

Figures 8.59 to 8.62 show moderate correlation coefficients of the living room residuals and residuals of adjacent zones, namely: bedroom 2, hallway, roof space and subfloor. Table 8.30 shows the fitted residuals of bedroom 2, hallway, roof space and subfloor at selected living room residuals.

Table 8.30: Fitted values of bedroom 2, hallway, roof space and subfloor residuals at selected living room residuals in the 5-star timber floor house

Residuals (ºC) *				
Living Room	Bedroom 2	Hallway	Roof Space	Subfloor
-6	-8.51	-15.96	-17.51	-5.70
-4	-6.33	-12.15	-13.16	-4.67
-2	-4.15	-8.34	-8.81	-3.63
0	-1.97	-4.54	-4.45	-2.60
+2	+0.21	-0.73	-0.10	-1.57
+4	+2.39	+3.08	+4.25	-0.54
+6	+4.58	+6.89	+8.60	+0.50

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Table 8.30 shows that the magnitude of residuals is always greater in the hallway and roof space than in the living room. For example, when the software over-predicted temperature in the living room by 6ºC, it over-predicted temperature in the hallway by 15.96ºC and in the roof space by 17.51ºC. Conversely, when the software under-predicted temperature in the living room by 6ºC, it under-predicted temperature in the hallway by 6.89ºC and in the roof space by 8.6ºC.

Residuals in the subfloor show that the software mostly over-estimated temperatures. The residuals for the living room and the subfloor are similar when the software over-estimated temperature, but dissimilar when the software under-predicted temperatures. When the software over-predicted temperature in the living room by 6ºC, it over-predicted temperatures in the subfloor by 5.7ºC, and when the software under-predicted temperature in the living room by 6ºC, it under-predicted temperature in the subfloor by 0.5ºC.

For the adjacent zones, bedroom 2 residuals are most similar to living room residuals considering both magnitude and direction.

4) Correlation between Living Room Residuals and Climate Parameters

Figures 8.63 to 8.66 show the scatterplot of living room residuals and the external climate parameters, namely: external air temperature, global solar radiation, wind speed and wind direction.

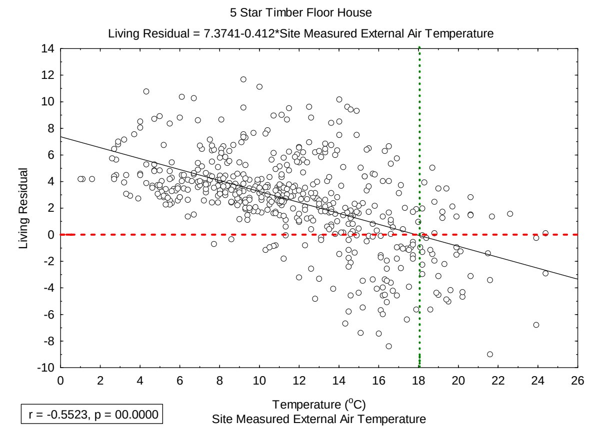


Figure 8.63: Scatterplot of living room residuals and external air temperature of the 5-star timber floor house

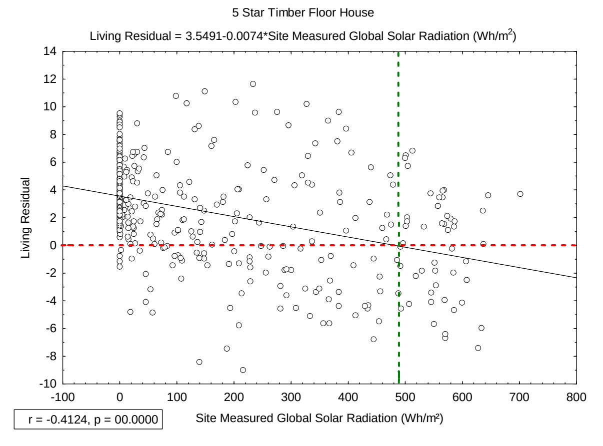


Figure 8.64: Scatterplot of living room residuals and global solar radiation of the 5-star timber floor house

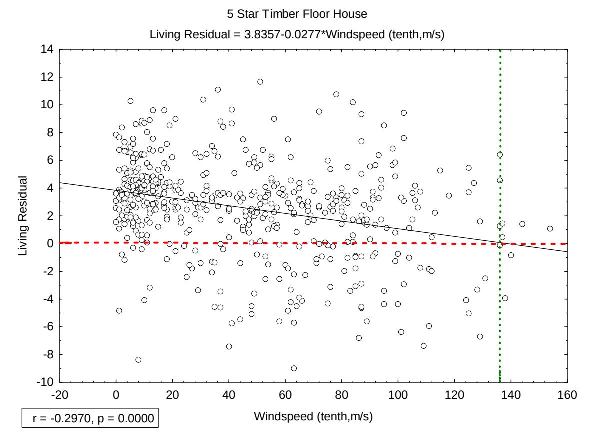


Figure 8.65: Scatterplot of living room residuals and wind speed of the 5-star timber floor house

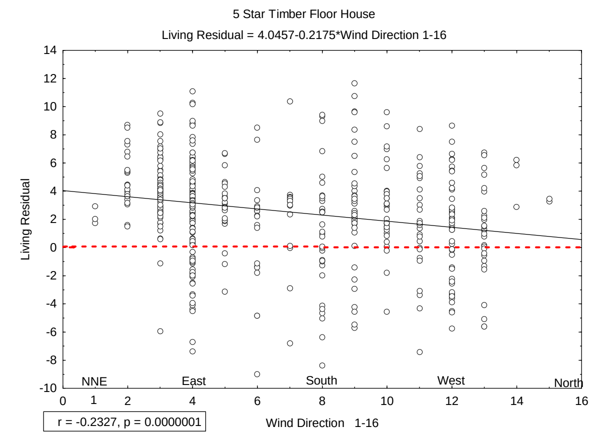


Figure 8.66: Scatterplot of living room residuals and wind direction of the 5-star timber floor house

Figure 8.63 shows that external temperatures and living room residuals had a moderate negative correlation coefficient of -0.5523. This figure also shows that the software is under-predicting living room temperatures at lower external temperatures, the magnitude of which decreases until an external temperature of 18ºC is reached. Above the external temperature of 18ºC, the living room temperatures were over-predicted. Residuals increase with the amount of over and under-prediction of the living room temperatures. Table 8.31 shows the fitted living room temperature residuals at selected external temperatures.

Table 8.31: Fitted living room residuals at selected external temperatures in the 5-star timber floor house

External Temperature (ºC)	5-Star Timber Floor House Living Room Residuals (ºC) *
2	+6.55
6	+4.90
10	+3.25
14	+1.61
18	+0.04
22	-1.69
26	-3.34

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Table 8.31 shows that at an external temperature of 2ºC, the software under-predicted temperature by 6.55ºC, and at an external temperature of 26ºC it over-predicted temperature by 3.34ºC. The living room residuals are close to zero at an external temperature of 18ºC.

Figures 8.64 to 8.66 show very low negative correlation coefficients for living room residuals versus: global solar radiation, wind speed and wind direction, indicating a very weak to no linear relationship between the living temperature and global solar radiation, wind speed and wind direction.

b) Bedroom 1

1) Correlation of Simulated and Measured Temperature for Bedroom 1

The scatterplot of simulated and measured temperatures for bedroom 1 is shown in Figure 8.67.

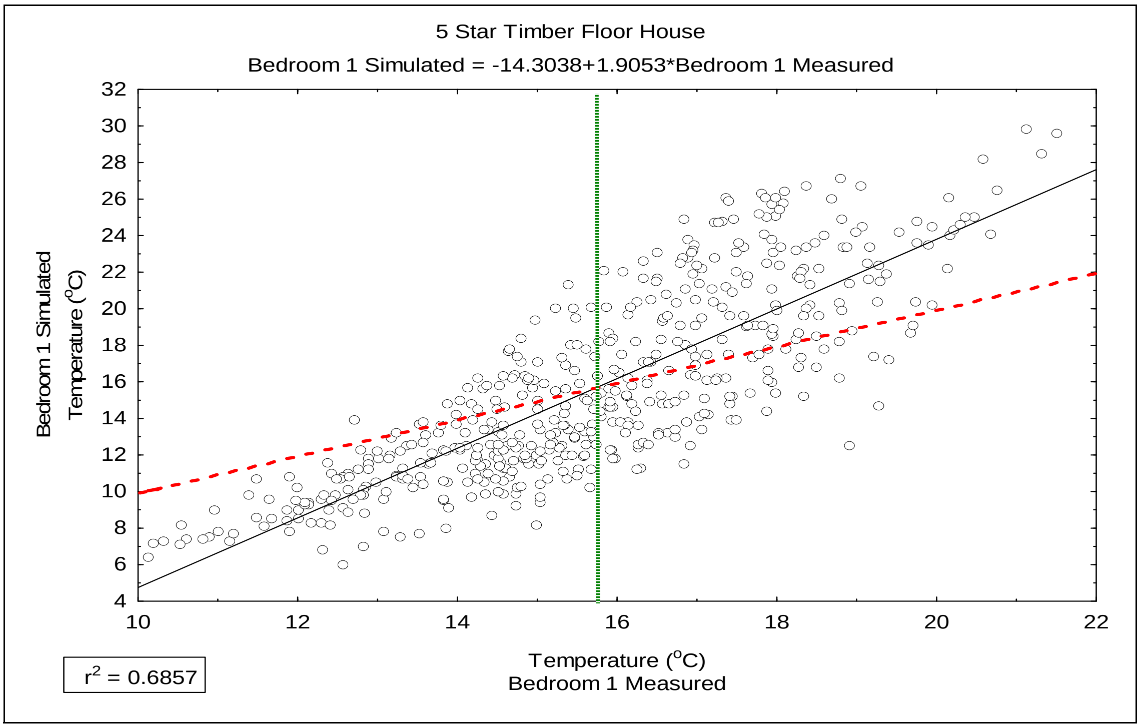


Figure 8.67: Scatterplot of simulated and measured temperatures for bedroom 1 of the 5-star timber floor house

Bedroom 1 measured and simulated temperatures have a moderate linear correlation with an r^2 of 0.6857. The line of best fit converges with the perfect line at the measured temperature of 15.8ºC. Below the measured temperature of 15.8ºC the software under-predicted room temperatures and above 15.8ºC the software over-predicted temperatures. Software predictions were closest to measured values around the measured temperatures of 15.8ºC. Table 8.32 describes the fitted simulated temperatures and corresponding residuals at measured temperatures of 10ºC to 20ºC.

Table 8.32: Fitted simulated temperatures and at various measured temperatures in bedroom 1 of the 5-star timber floor house

Measured Temperature (ºC)	Simulated Temperature (ºC)	Residual Temperature (ºC) *
10	4.7	+5.3
12	8.56	+3.44
14	12.37	+1.63
16	16.18	-0.18
18	19.99	-1.99
20	23.80	-3.80

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Table 8.32 shows that the software under-predicted temperatures in the measured temperature range of 10ºC to 14ºC by 1.63 to 5.3ºC respectively, and over-predicted temperature in the measured temperature range of 16ºC to 20ºC by 0.18 to 3.8ºC respectively.

2) Distribution of Temperature Residuals for Bedroom 1

The histogram of temperature residuals for bedroom 1 of the 5-star timber floor house is shown in Figure 8.68. The figure shows that residuals are normally distributed.

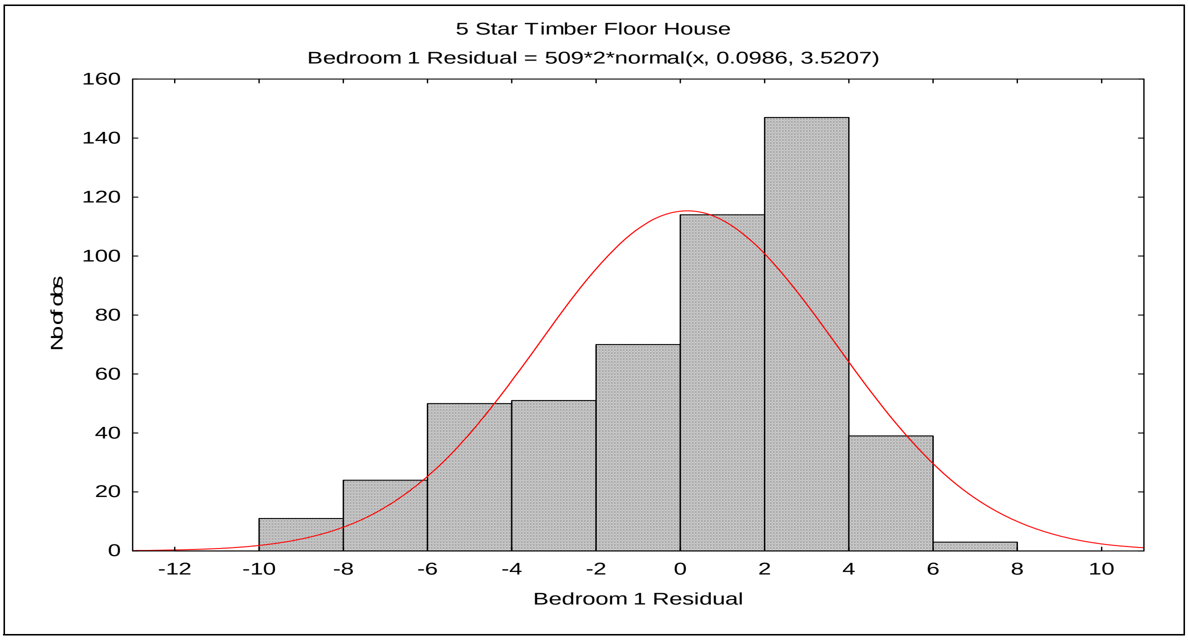


Figure 8.68: Distribution of residuals for bedroom 1 of the 5-star timber floor house

Figure 8.68 shows that the software under-predicted temperatures by as much as 2ºC to 4ºC for 148 hours or 29.1% of the time. Overall, the software under-predicted temperature for 308 hours, or by 60.9% of the time. Simulations also over-predicted temperature residuals at the range of 0ºC to 2ºC for 70 hours, or 13.8% of the time. Overall, the software over-predicted temperature for 201 hours, or 39.1% of the time.

3) Analysis of Temperature Residuals of Adjoining Zones

Figures 8.69 to 8.72 show the scatterplot of temperature residuals of bedroom 1 versus the residuals of the adjoining zones, namely: bedroom 1, hallway, roof space and subfloor.

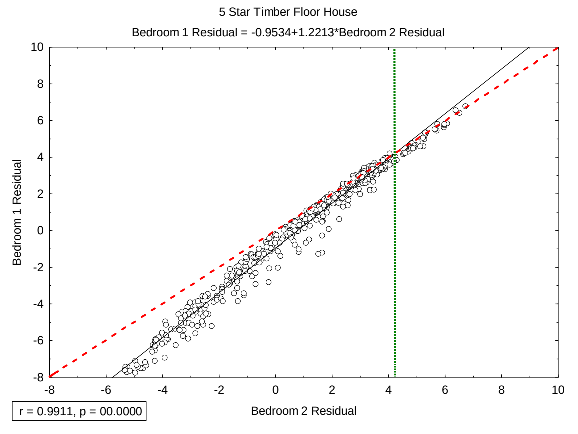


Figure 8.69: Scatterplot of bedroom 1 and bedroom 2 residuals of the 5-star timber floor house

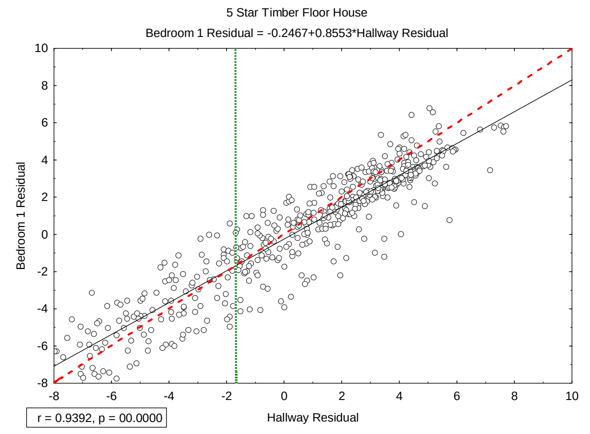


Figure 8.70: Scatterplot of bedroom 1 and hallway residuals of the 5-star timber floor house

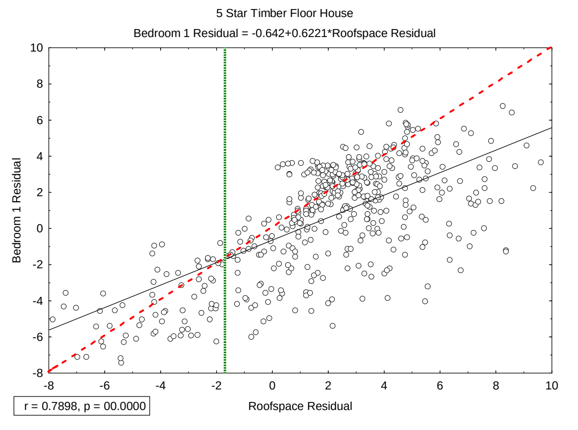


Figure 8.71: Scatterplot of bedroom 1 and roof space residuals of the 5-star timber floor house

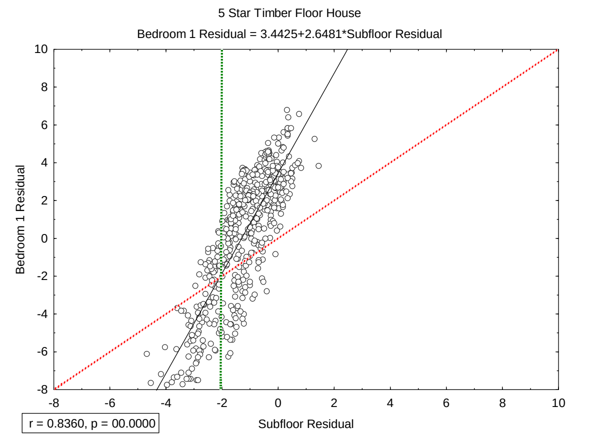


Figure 8.72: Scatterplot of bedroom 1 and subfloor residuals of the 5-star timber floor house

Figure 8.69 and 8.70 show very high correlation coefficients of 0.9911 and 0.9392, while the correlation coefficients in Figure 8.71 and 8.72 are moderate. Table 8.33 summarises the comparison of fitted residuals of bedroom 2, hallway, roof space and subfloor, at selected temperature residuals at bedroom 1.

Table 8.33: Fitted values of bedroom 2, hallway, roof space and subfloor residuals at selected bedroom 1 residuals in the 5-star timber floor house

Residuals (ºC) *				
Bedroom 1	Bedroom 2	Hallway	Roof Space	Sub Floor
-6	-4.13	-6.73	-8.61	-3.52
-4	-2.49	-4.39	-5.40	-2.77
-2	-0.86	-2.05	-2.18	-2.03
0	+0.78	+0.29	+1.03	-1.28
+2	+2.42	+2.63	+4.25	-0.54
+4	+4.06	+4.97	+7.46	+0.21
+6	+5.69	+7.30	+10.68	+0.95

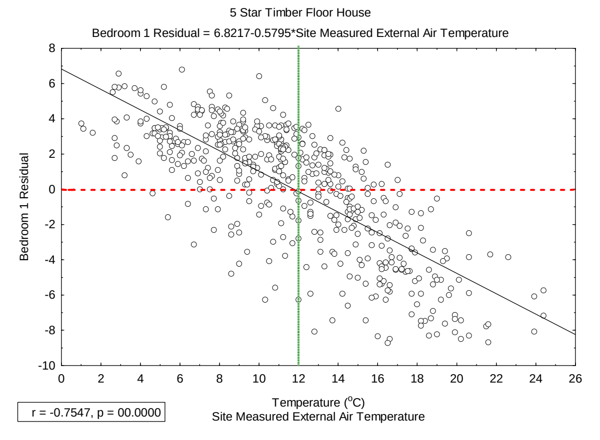
*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Table 8.33 shows similar trends in over and under-prediction of bedroom 1 residuals and the residuals of bedroom 2, hallway and the roof space. However, the trend differs for the subfloor, where the software mostly over-predicted temperatures. The magnitude of residuals is always greater in the hallway and roof space than in bedroom 1. For instance, when the software over-predicted temperatures in bedroom 1 by 6ºC, it over-predicted temperature in the hallway by 6.73ºC and in the roof space by 8.61ºC. Conversely, when the software under-predicted temperature in bedroom 1 by 6ºC, it under-predicted temperature in the hallway by 7.3ºC and in the roof space by 10.68ºC. The magnitude of residuals is most similar in bedroom 1 and bedroom 2. In terms of both magnitude and direction, the residuals in the hallway are most similar to bedroom 1 residuals.

4) Correlation of Bedroom 1 Residuals and Various Climate Parameters

Figures 8.73 to 8.76 show the scatterplots of bedroom 1 residuals versus the external climate parameters, namely: external air temperature, global solar radiation, wind speed and wind direction.

Figure 8.73 shows that the correlation of bedroom 1 and the external temperature is moderate, with a correlation ratio 0.7547. Figures 8.74 to 8.76 show a very low correlation coefficient for bedroom 1 residuals and the external climate parameters of global radiation, wind speed and wind direction, indicating that these climate factors had a very weak linear relationship to the bedroom 1 residuals.



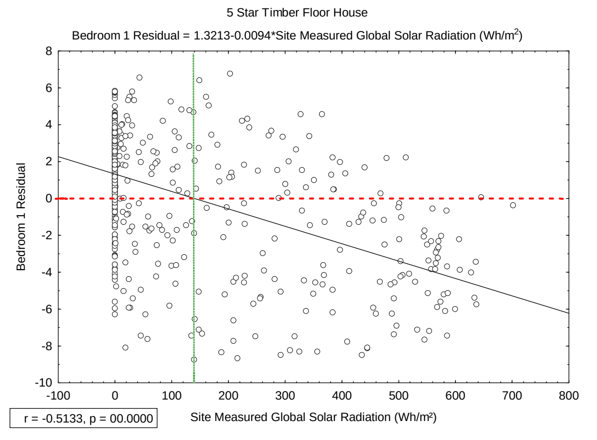
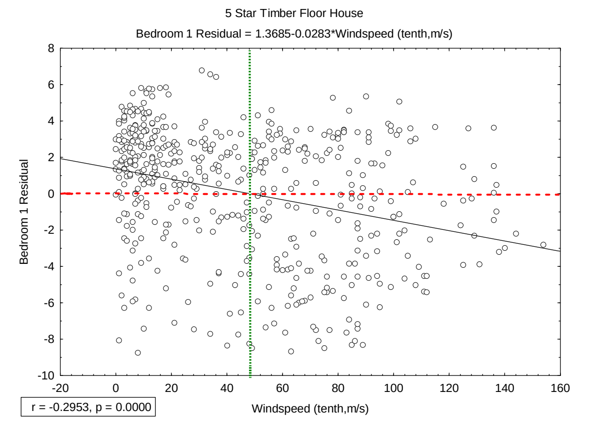


Figure 8.73: Scatterplot of bedroom 1 residuals and external air temperature of the 5-star timber floor house

Figure 8.74: Scatterplot of bedroom 1 residuals and global solar radiation of the 5-star timber floor house



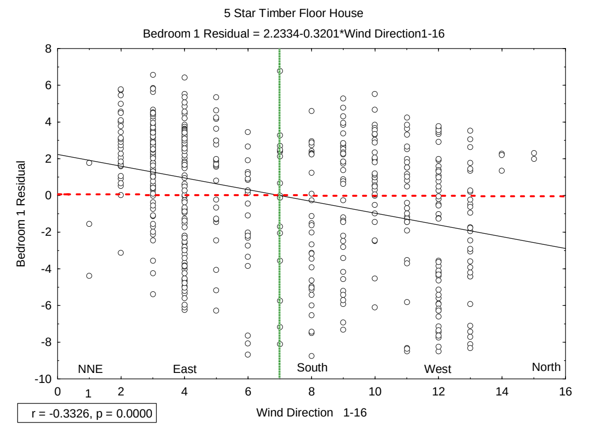


Figure 8.75: Scatterplot of bedroom 1 residuals and wind speed of the 5-star timber floor house

Figure 8.76: Scatterplot of bedroom 1 residuals and wind direction of the 5-star timber floor house

Figure 8.73 shows that the software under-predicts bedroom 1 temperatures at lower external temperatures, an amount which decreased until an external temperature of 12ºC, after which the software over-predicted bedroom 1 temperatures. Table 8.34 summarises the fitted bedroom 1 residuals at selected external temperatures.

Table 8.34: Fitted values of bedroom 1 residuals at selected external air temperatures in the 5-star timber floor house

External Temperature (ºC)	5-Star Timber Floor House Bedroom 1 Residuals (ºC) *
2	+5.66
6	+3.34
10	+1.02
12	+ 0.13
14	-1.20
18	-3.61
22	-5.93
26	-8.25

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Table 8.34 shows that at a low external temperature of 2ºC, the software under-predicted temperature by 5.66ºC and at higher external temperature of 26ºC, the software over-predicted temperature by 8.25ºC. At an external temperature of 12ºC the software prediction was close to the measured temperature, when it over-predicted only by 0.13ºC. Figures 8.75 to 8.76 show low correlation coefficients for the bedroom 1 residuals versus wind speed and wind direction, and this indicates that they had weak linear relations with the bedroom 1 residuals.

8.4.4. The 4-Star Timber Floor House

a) Living Room

1) Correlation of Simulated and Measured Temperature for the Living Room

The scatterplot of simulated and measured temperatures for the living room is shown in Figure 8.77.

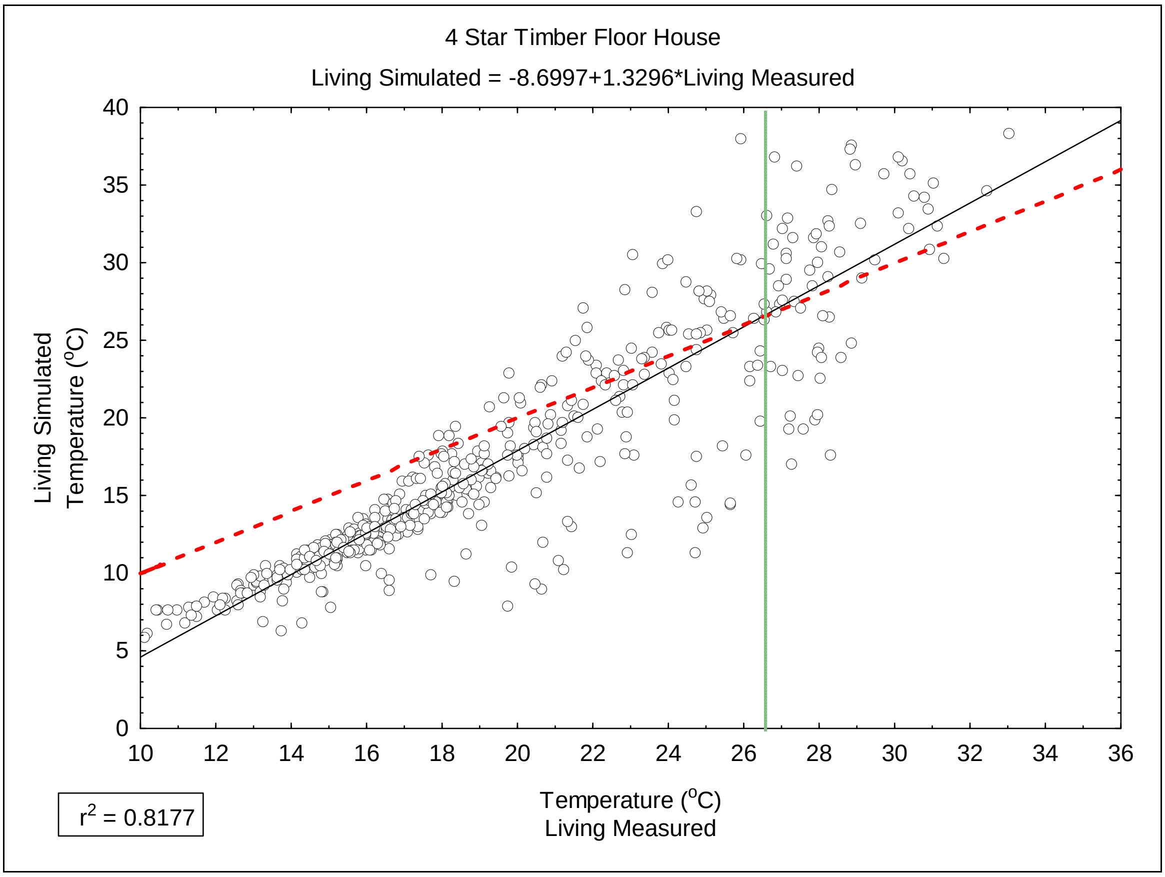


Figure 8.77: Scatterplot of simulated and measured temperatures for the living room of the 4-star timber floor house

The correlation of living room measured and simulated temperature is moderate, with an r^2 of 0.817. The data is closely grouped around the best-of-fit line between the measured temperatures of 10ºC to 19ºC. Over 19ºC the data is more scattered. The best fit line converges with the perfect fit line at the measured temperature of 26.4ºC. Below 26.4ºC the software under-predicted room temperature and above 26.4ºC the software over-predicted temperature. Table 8.35 summarises the fitted simulated temperatures and corresponding residuals at various measured temperatures.

Table8.35: Fitted values of simulated temperatures and corresponding residuals at various measured temperatures in the living room in the 4-star timber floor house

Measured Temperature ºC	Simulated Temperature ºC	Residual Temperature (ºC) *
10	4.60	+5.4C
14	9.91	+4.09
18	15.23	+2.77
22	20.55	+1.45
26	25.86	+0.14
30	31.18	-1.18

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Table 8.35 shows that the software under-predicted temperatures in the measured range of 10ºC to 26ºC by 0.14ºC to 5.4ºC respectively, and over-predicted temperature in the measured temperature of 30ºC by 1.18ºC. Temperature predictions were closest at higher measured temperatures of 22ºC to 26ºC.

2) Distribution of Residuals for the Living Room

Figure 8.78 shows the histogram of temperature residuals for the living room. The residuals are normally distributed.

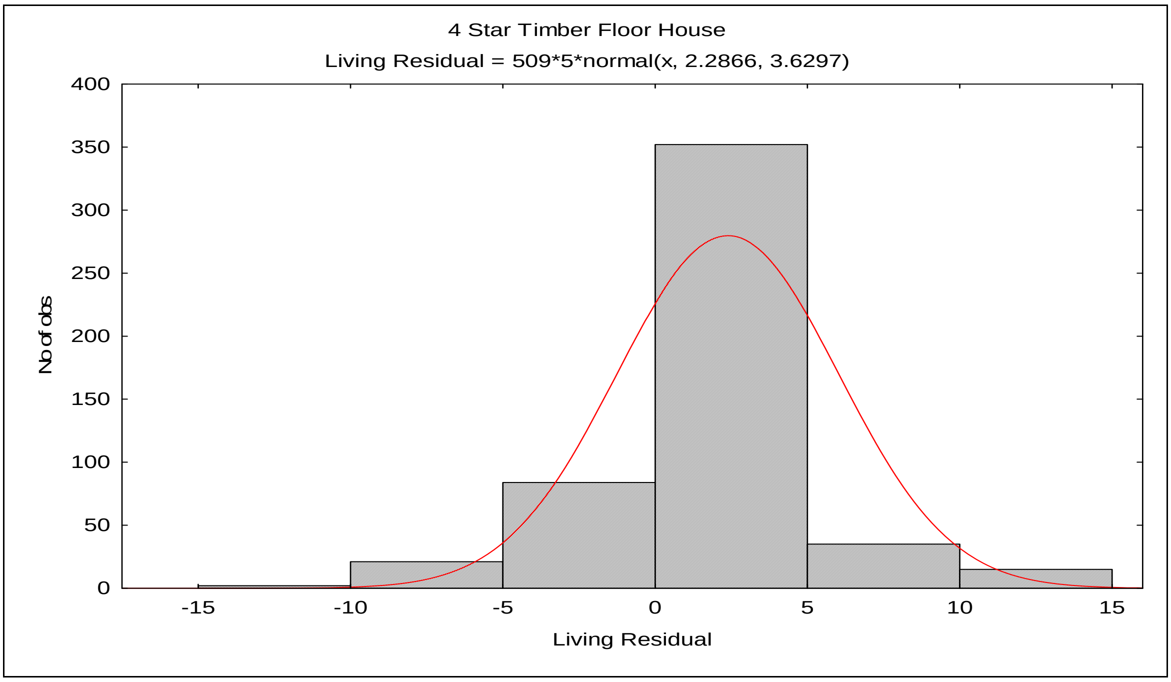


Figure 8.78: Distributions of residuals for the living room of the 4-star timber floor house

The software under-predicted temperatures in the living room by 0ºC to 5ºC for 350 hours, or 68.8% of the time. Overall, the software under-predicted temperature in the living room for 410 hours, or 80.8% of the time. Simulations also over-predicted temperatures by 0ºC to 5ºC for 90 hours, or 17.7% of time. Overall, the software over-predicted temperatures for 99 hours or 19.4% of the time.

3) Analysis of Temperature Residuals of Adjoining Zones

Figures 8.79 to 8.82 show the scatterplots of residuals of the living room and adjoining zones of bedroom 2, hallway, roof space and subfloor.

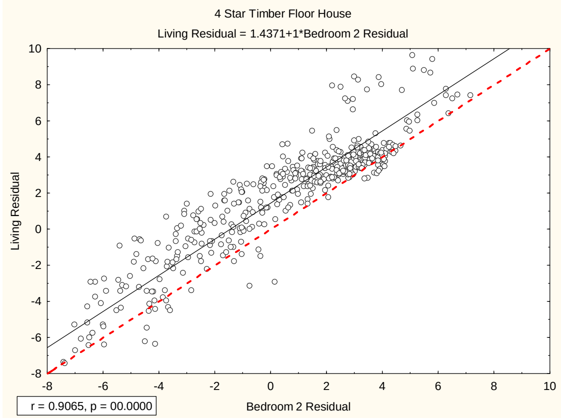


Figure 8.79: Scatterplot of the living room and bedroom 2 residuals of the 4-star timber floor house

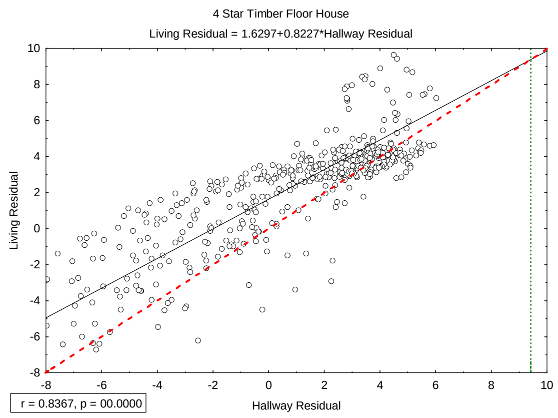


Figure 8.80: Scatterplot of the living room and hallway residuals of the 4-star timber floor house

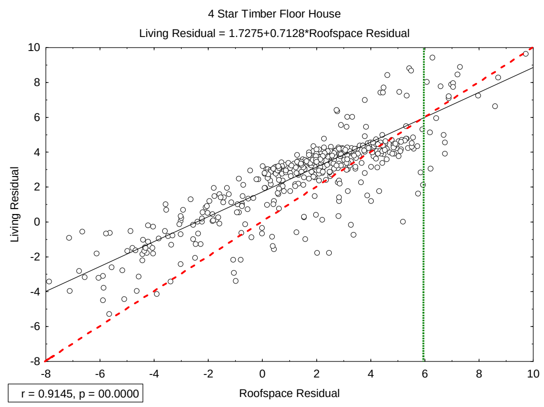


Figure 8.81: Scatterplot of the living room and roof space residuals of the 4-star timber floor house

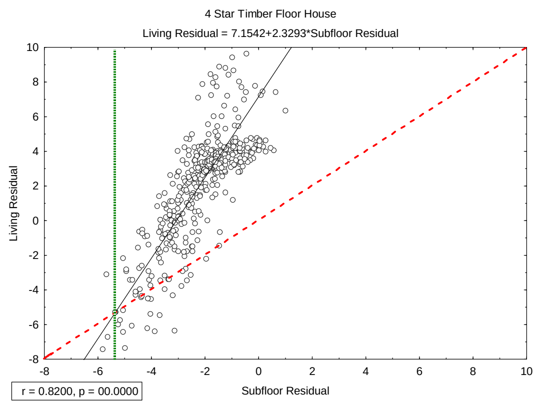


Figure 8.82: Scatterplot of the living room and subfloor residuals of the 4-star timber floor house

Figures 8.79 to 8.82 show high correlation coefficients of the living room residuals versus the residuals of bedroom 2, hallway, roof space and subfloor. Table 8.36 shows the fitted residuals of bedroom 2, hallway, roof space and subfloor at selected living room residuals.

Table 8.36: Fitted values bedroom 2, hallway, roof space and subfloor residuals at selected living room residuals in the 4-star timber floor house

Residuals (ºC) *				
Living Room	Bedroom 2	Hallway	Roof Space	Sub Floor
-6	-7.44	-9.35	-10.84	-2.99
-4	-5.44	-6.92	-8.04	-2.15
-2	-3.44	-4.49	-5.23	-1.32
0	-1.44	-2.06	-2.42	-0.48
+2	+0.56	+0.37	+0.38	+0.35
+4	+2.56	+2.80	+3.19	+1.19
+6	+4.56	+5.24	+6.00	+2.03

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Table 8.36 shows similar trends of over and under-prediction for the living room and its adjacent zones, namely: bedroom 2, hallway, roof space and subfloor. The range of residuals is smallest in the subfloor. For example, when the software over-predicted temperature in the living room by 6ºC it over-predicted temperature in the subfloor by 2.99ºC, and when the software under-predicted temperature in the living room by 6ºC, it under-predicted temperature in the subfloor by 2.03ºC. The magnitude of over-predicted temperatures is greatest in the roof space. For instance, when the software over-predicted temperature in the living room by 6ºC, it over-predicted temperature in the roof space by 10.84ºC. When the software under-predicted temperature in the living room by 6ºC, it under-predicted temperature in the roof space by 6ºC. The magnitude of residuals is closest between the living room and bedroom 2 residuals.

4) Correlation of Living Room Residuals and Climate Parameters

Figures 8.83 to 8.86 show the scatterplots of living room residuals versus the climate parameters, namely: the external air temperature, global solar radiation, wind speed and wind direction.

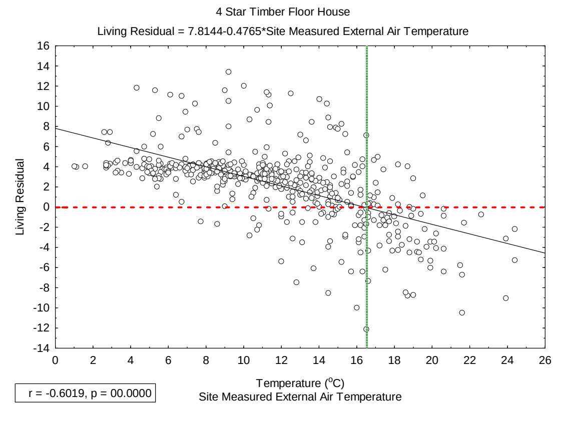


Figure 8.83: Scatterplot of living room residuals and external air temperature of the 4-star timber floor house

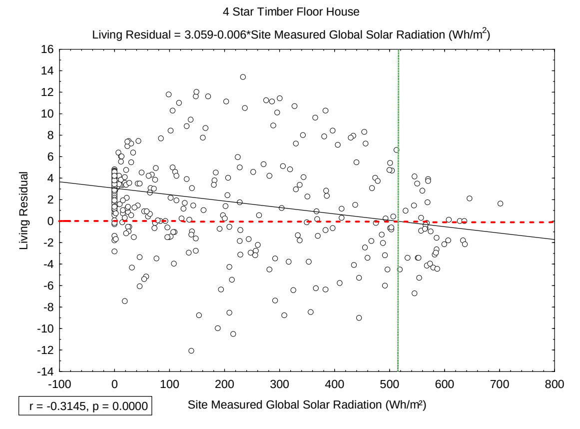


Figure 8.84: Scatterplot of living room residuals and global solar radiation of the 4-star timber floor house

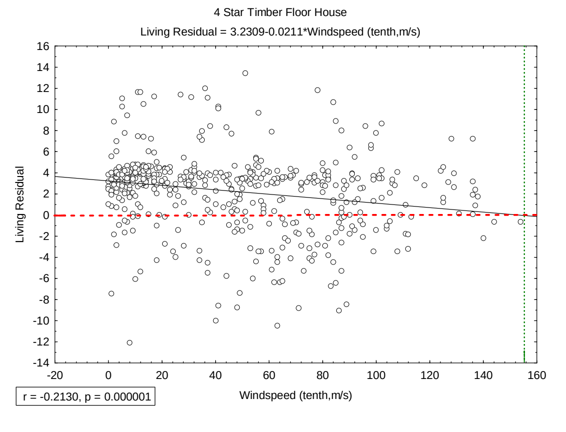


Figure 8.85: Scatterplot of living room residuals and wind speed of the 4-star timber floor house

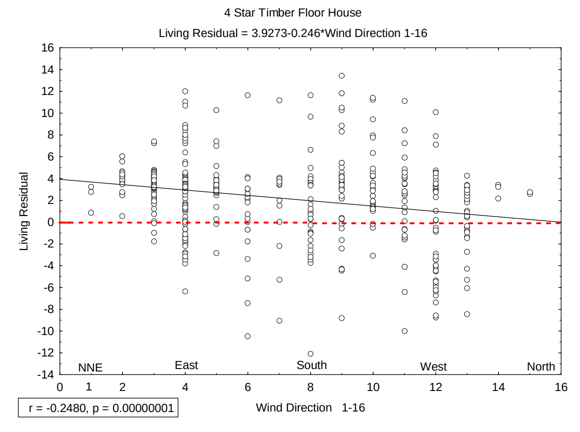


Figure 8.86: Scatterplot of living room residuals and wind direction of the 4-star timber floor house

Figure 8.83 shows a moderate negative correlation coefficient of -0.6019. This figure also shows that the software is under-predicting living room temperatures at lower external temperatures up to 16.5ºC. Above the external temperature of 16.5ºC the living room temperatures are over-predicted. Residuals increase with the amount of over and under-prediction of the living room temperatures.

Table 8.37 summarises the fitted residuals of the living room at selected external temperatures in the 4-star timber floor house.

Table 8.37: Fitted values of living room residuals at selected external temperatures in the 4-star timber floor house

External Temperature (ºC)	4-Star Timber Floor House Living Room Residuals (ºC) *
2	+6.86
6	+4.96
10	+3.05
14	+1.14
16	+0.19
18	-0.76
22	-2.67
26	-4.57

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Table 8.37 shows that at an external temperature of 2ºC the software under-predicted temperature in the Living room by 6.86ºC and at an external temperature of 26ºC the software over-predicted temperature by 4.57ºC. The magnitude of under-prediction is greater than the magnitude of over-prediction. For instance, the software under-predicted temperature by 0.19ºC to 6.86ºC, and over-predicted temperature by 0.76ºC to 4.57ºC. The living room residual is smallest at an external temperature of 16ºC, when the software under-predicted temperature by 0.19ºC.

Figures 8.84 to 8.86 indicate very low negative correlation coefficients of the living room residuals and global solar radiation, wind speed and wind direction. This indicates that these climate parameters had only very weak relationship to the living room residuals.

b) Bedroom 1

<u>1) Correlation of Simulated and Measured Temperature for Bedroom 1</u>

Figure 8.87 shows the correlation between simulated and measured temperatures for bedroom 1.

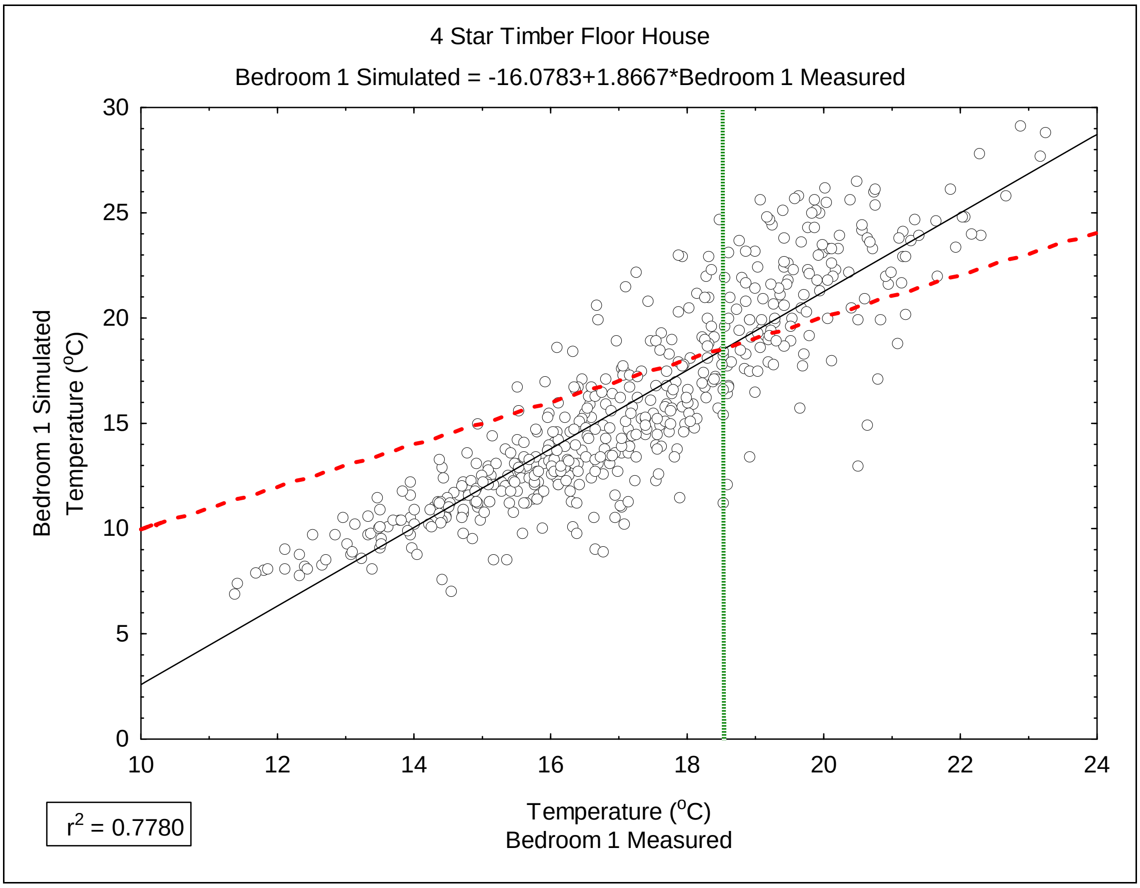


Figure 8.87: Scatterplot of simulated and measured temperature for bedroom 1 of the 4-star timber floor house

The correlation of bedroom 1 measured and simulated temperatures are moderate with an r^2 of 0.7780. The data is concentrated around the trend line between 14ºC and 18ºC. Above 18ºC data become more scattered. The line of-best-fit line intersects with the perfect-fit line at 18.5ºC, below this value the software under-predicted room temperature, and above 18.5ºC, the software over-predicted temperatures. Table 8.38 summarises the fitted simulated temperatures at measured temperatures between 10ºC and 22ºC.

Table 8.38: Fitted values of simulated temperatures and at various measured temperatures in bedroom 1 of the 4-star timber floor house

Measured Temperature (ºC)	Simulated Temperature (ºC)	Residual Temperature (ºC) *
10	2.29	+7.41
12	6.32	+5.68
14	10.06	+3.94
16	13.79	+2.21
18	17.52	+0.48
20	21.26	-1.26
22	24.99	-2.99

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Table 8.38 shows that at measured temperature of 10ºC the software under-predicted bedroom 1 temperature by 7.41ºC, and at measured temperature of 22ºC the software over-predicted temperature by 2.99ºC. The under-prediction of 7.41ºC at the measured temperature of 10ºC is significantly larger than the over-prediction of 2.99ºC at the measured temperature of 22ºC. At 18.5ºC simulated and measured temperatures are equal (Figure 8.87).

2) Distribution of Temperature Residuals for Bedroom 1

The histogram of temperature residuals for bedroom 1 is shown in Figure 8.88. The residuals are normally distributed.

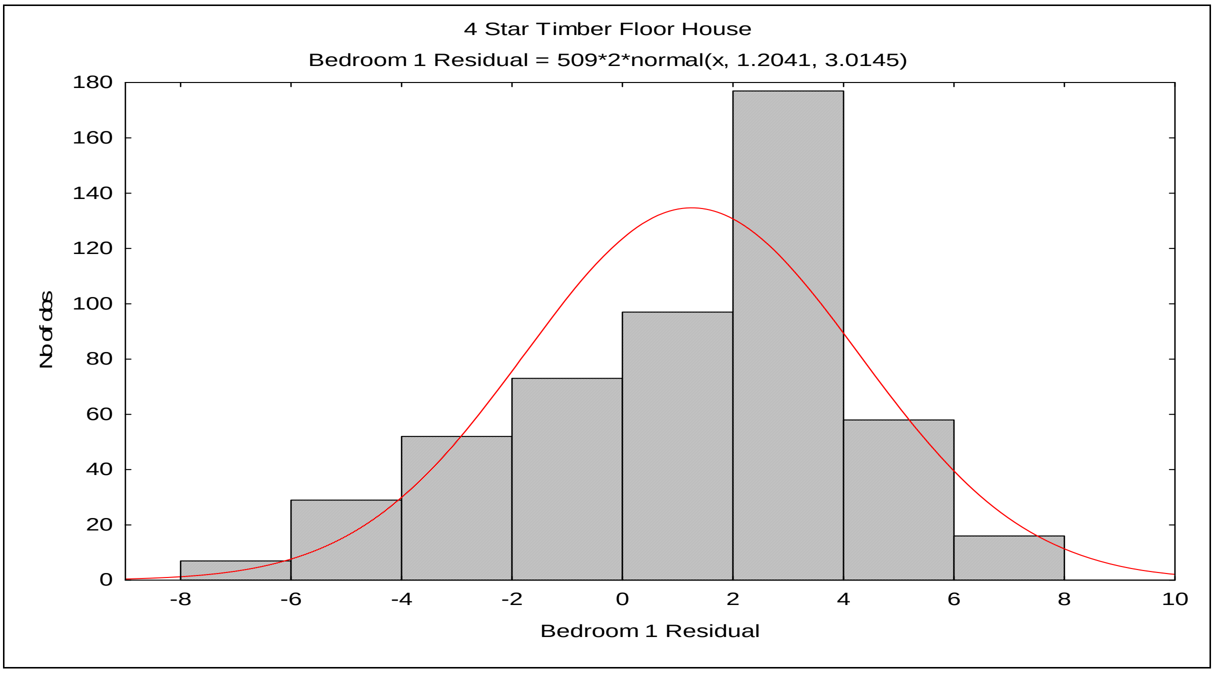


Figure 8.88: Distribution of residuals in Bedroom 1 of the 4-star timber house

The software under-predicted temperatures of 2ºC to 4ºC for 178 hours, or 34.9% of time. Overall, the software under-predicted temperatures 68.8% of the time. Simulations also over-predicted temperatures by 2ºC for 72 hours or 14.1% of time. Overall, the software over-predicted temperature 31.2% of time.

3) Analysis of Temperature Residuals of Adjoining Zones

Figure 8.89 to 8.92 show the scatterplots of temperature residuals for the bedroom 1 versus the residuals of bedroom 2, hallway, roof space and subfloor.

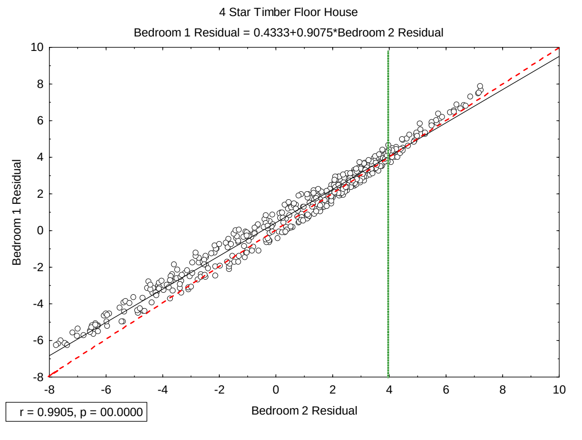


Figure 8.89: Scatterplot of bedroom 1 and bedroom 2 residuals of the 4-star timber floor house

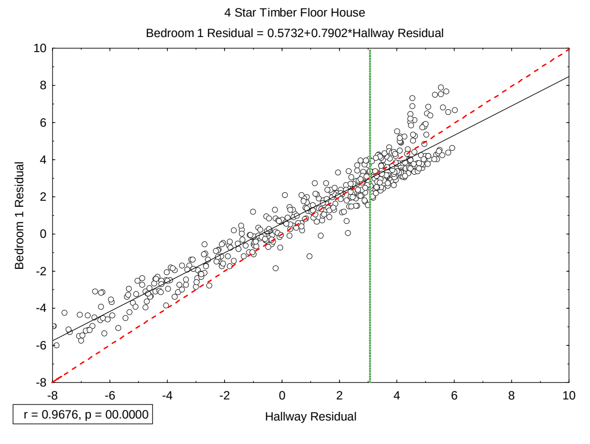


Figure 8.90: Scatterplot of bedroom 1 and hallway residuals of the 4-star timber floor house

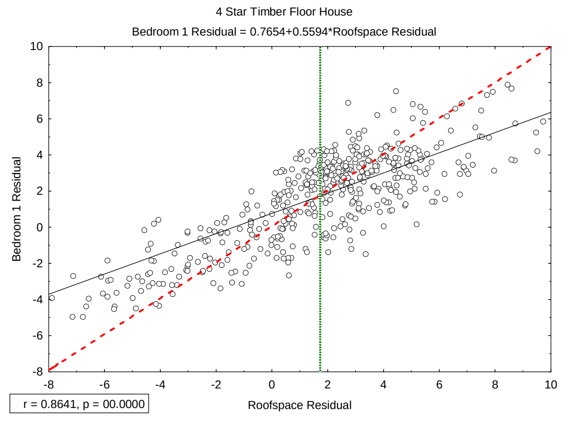


Figure 8.91: Scatterplot of bedroom 1 and roof space residuals of the 4-star timber floor house

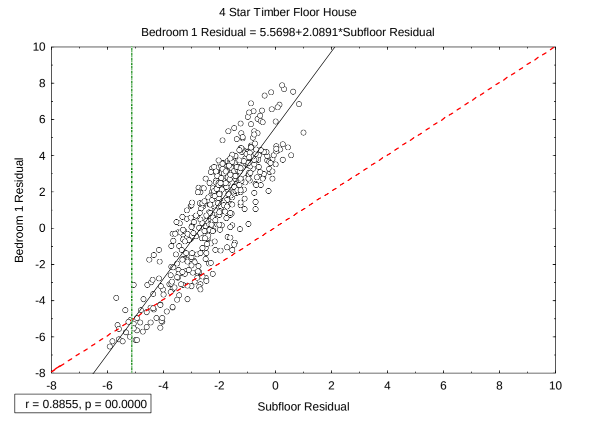


Figure 8.92: Scatterplot of bedroom 1 and subfloor residuals of the 4-star timber floor house

The scatterplots of temperature residuals of bedroom 1 versus the adjacent zones of bedroom 2, hallway, roof space and subfloor show high correlation coefficients. Table 8.39 summarises the fitted residuals of bedroom 2, hallway, roof space and subfloor at selected bedroom 1 residuals.

Table 8.39: Fitted values of bedroom 2, hallway, roof space and subfloor residuals at selected bedroom 1 residuals for the 4-star timber floor house

Residuals (ºC) *				
Bedroom 1	Bedroom 2	Hallway	Roof Space	Sub Floor
-6	-7.09	-8.32	-12.09	-5.54
-4	-4.89	-5.79	-8.52	-4.58
-2	-2.68	-3.26	-4.94	-3.62
0	-0.48	-0.73	-1.37	-2.67
+2	+1.70	+1.81	+2.21	-1.71
+4	+3.93	+4.34	+5.78	-0.75
+6	+6.13	+6.87	+9.36	+0.21

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Table 8.39 shows that the range of residuals is always greater in the hallway and in the roof space than in bedroom 1. For instance, when the software over-predicted temperature in bedroom 1, it over-predicted temperature in the roof space by 12.09ºC and in the hallway by 8.32ºC. When the software under-predicted temperature in bedroom 1 by 6ºC, it under-predicted temperature in the roof space by 9.36ºC and in the hallway by 6.87ºC.

The magnitude and direction of bedroom 1 and bedroom 2 residuals are quite similar. When the software over-predicted temperature in bedroom 1 by 6ºC, it over-predicted temperature in bedroom 2 by 7.09ºC and when the software under-predicted temperature by 6ºC in bedroom 1, it under-predicted temperature in bedroom 2 by 6.13ºC.

The magnitude of over-prediction in bedroom 1 and the subfloor are similar but not for the magnitude of under-prediction. For example, when the software under-predicted temperature in bedroom 1 by 6ºC, it under-predicted temperature in the subfloor by 5.54ºC and when the software under-predicted temperature in bedroom 1 by 6ºC, it under-predicted temperature in the subfloor by 0.21ºC. This table also shows that the software mostly over-predicted subfloor temperatures.

4) Correlation of Bedroom 1 Residuals and Climate Parameter

Figure 8.93 to 8.96 show the scatterplots of bedroom 1 residuals versus the external parameters of external air temperature, global solar radiation, wind speed and wind direction.

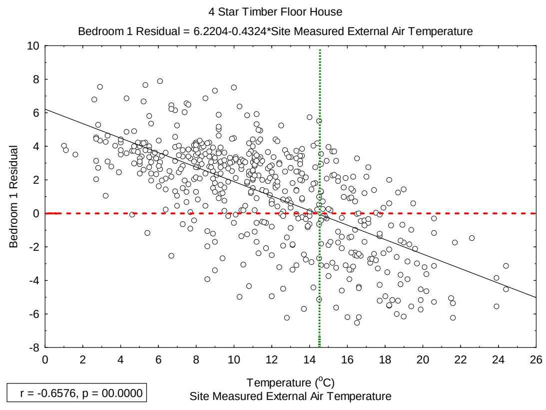


Figure 8.93: Scatterplot of bedroom 1 residuals and external air temperature of the 4-star timber floor house

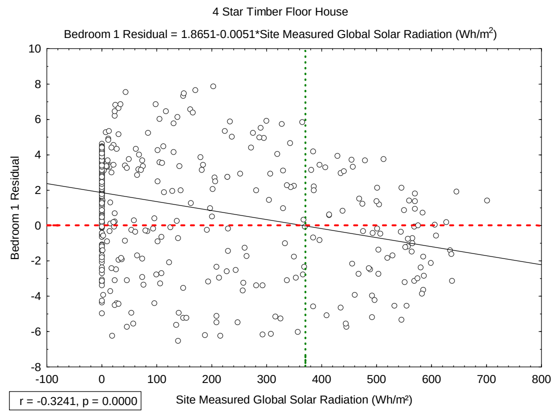


Figure 8.94: Scatterplot of bedroom 1 residuals and global solar radiation of the 4-star timber floor house

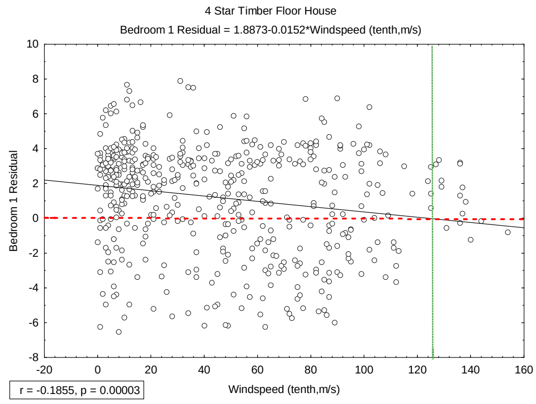


Figure 8.95: Scatterplot of bedroom 1 residuals and wind speed of the 4-star timber floor house

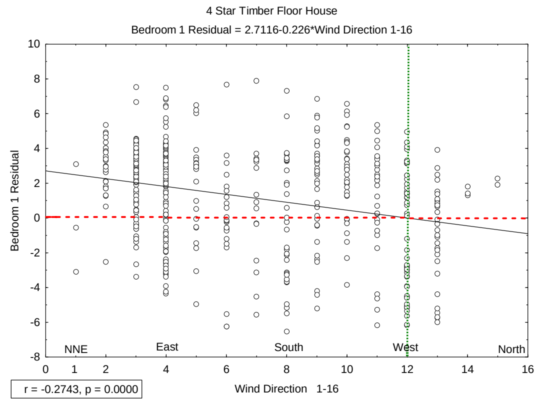


Figure 8.96: Scatterplot of bedroom 1 residuals and wind direction of the 4-star timber floor house

Figure 8.93 shows a moderate negative correlation coefficient of -0.6576 for bedroom 1 residuals and external air temperature. This figure also shows residuals in bedroom 1 under-predicted temperature below the external temperature of 14.5ºC. Above the external temperature of 14.5ºC the software over-predicted temperatures. The amount of residuals increases with the magnitude of over and under-prediction of temperatures. Table 8.40 shows the fitted bedroom 1 residuals at selected external air temperatures.

Table 8.40: Fitted values of living room residuals at selected external air temperatures in bedroom 1 of the 4-star timber floor house

External Temperature (ºC)	4-Star Timber Floor House Bedroom 1 Residuals (ºC) *
2	+5.36
6	+3.63
10	+1.90
14	+0.17
18	-1.56
22	-3.29
26	-5.02

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Table 8.40 shows that at an external air temperature of 2ºC the software under-predicted temperature by 5.36ºC, and at an external temperature of 26ºC, the software over-predicted temperature by 5.02ºC. The magnitude of over and under-prediction at the external temperatures of 2º C and 26ºC are similar. Residuals are close to zero at the external air temperature of around 14.5ºC (Figure 9.95).

Figures 8.94 to 8.96 show a low negative correlation of bedroom 1 residuals versus global solar radiation, wind speed and wind direction, and this indicates that these climate parameters had a very weak, to no linear correlation with the bedroom 1 residuals.

8.4.5. Comparison of the Three Test Houses

This section provides a comparison of statistical analyses results for temperature data of the slab floor house and the 5-star and 4-star timber floor house. This includes the following comparisons:

- Scatterplot of simulated and measured temperatures for the living room and bedroom 1;
- Distribution of residuals;
- Analysis of temperature residuals of adjoining zones;
- Correlation of living room and bedroom 1 residuals with external air temperatures.

a) Correlation of Simulated and Measured Temperatures of the three Houses

Figure 8.97 to 8.102 is a summary of all 6 scatterplots of the simulated and measured temperatures for the living room and bedroom 1 for the slab floor house, 5-star timber floor house and the 4-star timber floor house.

Living Room | **Bedroom 1**

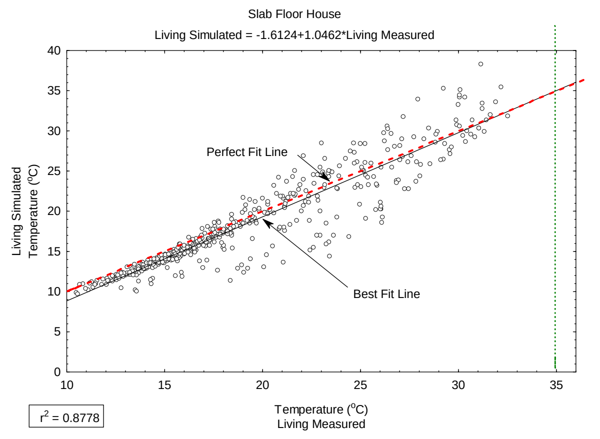


Figure 8.97: Scatterplot of simulated and measured temperatures for the living room of the slab floor house

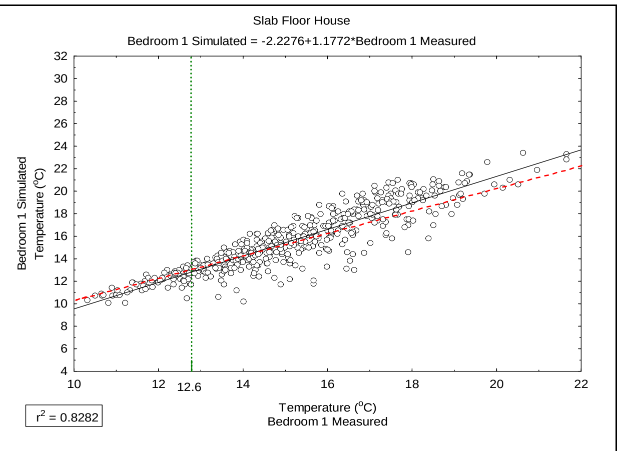


Figure 8.98: Scatterplot of simulated and measured temperatures for bedroom 1 of the slab floor house

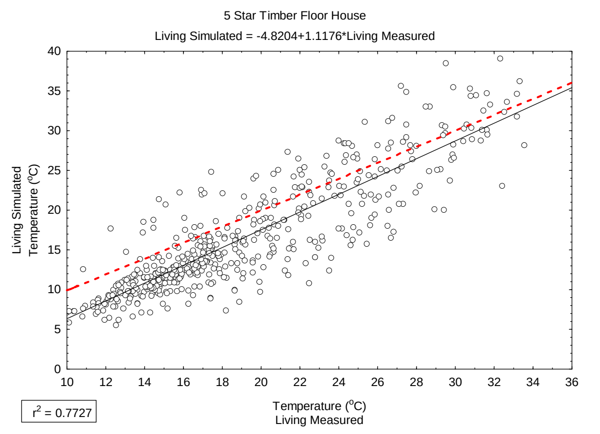


Figure 8.99: Scatterplot of simulated and measured temperatures for the living room of the 5-star timber floor house

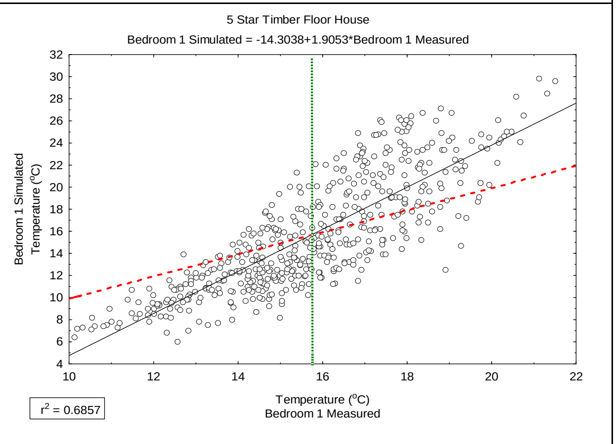


Figure 8.100: Scatterplot of simulated and measured temperatures for the bedroom 1 of the 5-star timber floor house

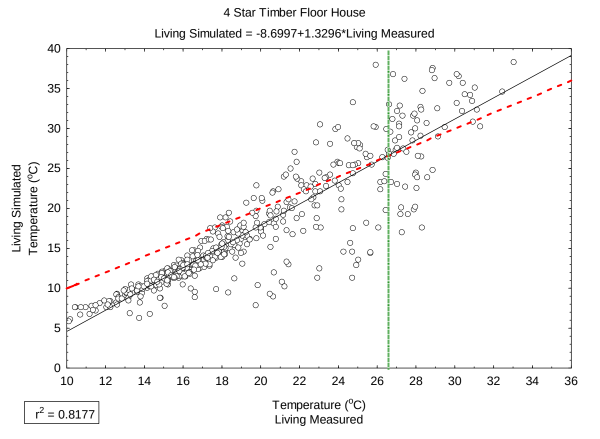


Figure 8.101: Scatterplot of simulated and measured temperatures for the living room of the 4-star timber floor house

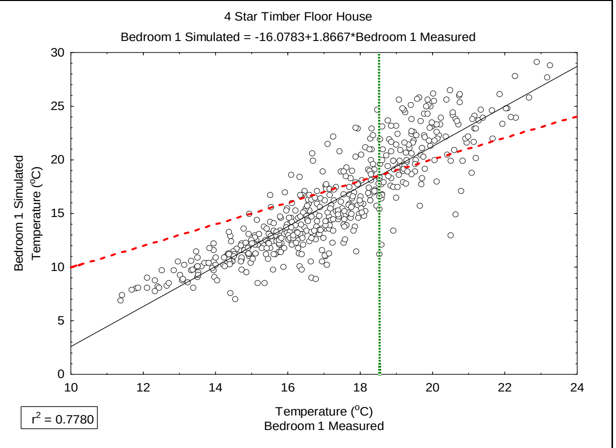


Figure 8.102: Scatterplot of simulated and measured temperatures for the bedroom 1 of the 4-star timber floor house

The correlation of the simulated and measured temperatures can be observed in the living room and bedroom 1 of the slab floor house, with an r^2 of 0.8778 in the living room and an r^2 of 0.8282 in bedroom 1. The correlation is weaker in bedroom 1 of the timber floor houses with an r^2 of 0.6857 in the 5-star, and 0.7780 in the 4-star timber floor house. It is noteworthy that the correlations of the simulated and measured temperatures are always greater in the living room than in bedroom 1, in all three houses.

The correlations are moderate to high in all zones indicating that the software model accounts for 70-90% of the variation in measured temperature profiles. However, the temperature levels generally do not match and these contributed to the variations between measured and simulated temperatures. Table 8.41 shows the comparison of fitted values of simulated temperatures for the measured temperature range of 10ºC to 30ºC.

Table 8.41: Comparison of residuals of simulated temperatures at various measured temperatures in the living room of the test houses

Measured Temperature (ºC)	Residuals of Living Room Simulated Temperatures (ºC) *		
	Slab Floor house	5-star Timber Floor House	4-star Timber Floor House
10	+1.15	+3.64	+5.40
14	+0.97	+3.17	+4.09
18	+0.78	+2.69	+2.77
22	+0.60	+2.23	+1.45
26	+0.41	+1.76	+0.14
30	+0.23	+1.29	-1.18

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

The smallest range of residuals is in the living room of the slab house, where the software is under-predicting the temperature between 0.23ºC to 1.15ºC, at the measured temperature range of 10ºC to 30ºC. The residuals are largest in the living room of the 4-star timber floor house. It is interesting to note that the software simulation generally under-predicted temperatures in the living rooms, except in the 4-star timber house at the measured temperatures of 30ºC, where the software over-predicted temperature in the living room.

Table 8.42 shows the fitted values of simulated temperatures for the measured temperature range of 10ºC to 20ºC for bedroom 1 of the three test houses.

Table 8.42: Comparison of residuals of fitted values of simulated temperatures at various measured temperatures in bedroom 1 of the three test houses

Measured Temperature (ºC)	Residuals Bedroom 1 Simulated Temperatures (ºC) *		
	Slab Floor house	5-star Timber Floor House	4-star Timber Floor House
10	+0.60	+5.3	+7.41
12	+0.10	+3.44	+5.68
14	-0.25	+1.63	+3.94
16	-0.67	-0.18	+2.21
18	-0.96	-1.99	+0.48
20	-1.32	-3.80	-1.26

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

The range of residuals is significantly smaller in bedroom 1 of the slab floor house than the timber floor houses. The software under-predicted temperatures by up to 0.6ºC and over-predicted temperature in the slab floor house by only up to 1.32ºC at a measured temperature range of 10ºC to 20ºC.

The magnitude of residuals is largest in the 4-star timber floor house between the measured temperatures of 10ºC to 16ºC. Above the measured temperature of 16ºC, the magnitude of residuals is largest in the 5-star timber floor house.

Overall, the software simulated temperatures are more accurate in the living room and bedroom 1 of the slab floor house than in the 5-star and 4-star timber floor houses.

b) Distribution of Residuals of the Three Test Houses

Table 8.43 shows the comparison of the proportion of time during the monitored period that the software under and over-predicted temperatures in each of the test houses.

Table 8.43: Comparison of percentage time of over and under-prediction for the test houses

House Zone	Slab Floor House	5-Star Timber Floor House	4-Star Timber Floor House
Living Room			
Under-prediction	82.5%	60.5%	78.5%
Over-prediction	17.5%	39.5%	21.5%
Bedroom 1			
Under-prediction	31%	59.9%	68.8%
Over-prediction	69%	40.1%	31.2%
Subfloor	-		
Under-prediction	-	11.1%	3.3%
Over-prediction		88.9%	96.7%
Roof Space			
Under-prediction	75.2%	74.7%	73.3%
Over-prediction	24.8%	25.3%	26.7%

The software generally under-predicted temperatures for most of the time in the living room, bedroom 1 and roof space of the houses, except for bedroom 1 of the slab floor house, where the software mostly over-predicted temperatures. Whereas the software over-predicted temperatures for most of the time in the subfloor of the timber floor houses (88.9% of the time in the 5-star timber floor house and for 96.7% of the time in the 4-star timber floor house). The significant amount of over-prediction of temperatures in the subfloor strongly suggests an examination of the subfloor model. Table 8.44 shows the comparison of the maximum positive (under-predicted) and negative (over-predicted) temperature residuals during the monitoring period in various zones namely, the living room, bedroom 1, hallway, roof space and the subfloor.

Table 8.44: Comparison of actual maximum positive and negative residuals during the monitoring period in the test houses

Zone	Slab Floor House		5-Star Timber Floor House		4-Star Timber Floor House	
	Maximum negative residuals (ºC) *	Maximum positive residuals (ºC) *	Maximum negative residuals (ºC) *	Maximum positive Residuals (ºC) *	Maximum negative residuals (ºC) *	Maximum positive residuals (ºC) *
Living Room	-7.14	+9.00	-9.00	+11.67	-12.09	+13.41
Bedroom 1	-3.46	+3.86	-8.73	+6.79	-6.53	+7.88
Hallway	-4.40	+3.66	-10.35	+7.70	-9.94	+6.02
Roof Space	-17.53	+10.08	-18.20	+10.58	-19.80	+10.52
Subfloor	-	-	-4.68	+1.43	-5.92	+1.00

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

The greatest residuals are in the roof space temperatures of all three houses. The widest range of residuals are in roof space of the 4-star timber house where the software over-predicted temperatures by as much as 19.8ºC and under-predicted temperatures by up to 10.5ºC.

The lowest maximum residuals occur in the subfloor of the timber floor houses where the software under-predicted maximum temperatures in the 5-star timber house by 1.43ºC and in the 4-star timber house by 1.0ºC. The maximum residuals are significantly less in the slab floor house. The range of residuals in the roof space is significant, and this strongly suggests an examination of the roof space model.

c) Correlation of Residuals between Adjoining Zones of the Test Houses

The temperature residuals of specific adjacent zones in the three houses are compared in this section, as follows:

- Living room with bedroom 2;
- Living room with the roof space;
- Living room with the subfloor (5-star and 4-star timber houses only);
- Bedroom 1 with bedroom 2;
- Bedroom 1 with the roof space;
- Bedroom 1 with the subfloor (5-star and 4-star timber houses only).

The following tables compare fitted residuals for the adjacent zones to the living room and bedroom 2 in all houses. Table 8.45 shows fitted bedroom 2 residuals at selected living room residuals for the three houses.

Table 8.45: Fitted values of bedroom 2 residuals at selected living room residuals for the three test houses

Living Room Residuals (ºC)	Bedroom 2 Residuals (ºC) *		
	Slab Floor House	5-Star Timber Floor House	4-Star Timber Floor House
-6	-5.23	-8.51	-7.44
-4	-3.64	-6.33	-5.44
-2	-2.04	-4.15	-3.44
0	-0.45	-1.97	-1.44
+2	+1.14	+0.21	+0.56
+4	+2.73	+2.39	+2.56
+6	+4.23	+4.58	+4.56

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

In general, the magnitude and direction in all three bedroom 2s are similar and are in the same direction as the living room residuals. Residual values in bedroom 2 of the slab floor house are lower in magnitude than the residuals of the living room. Residual values in bedroom 2 of the 5-star and 4-star timber houses are greater than the residuals of the living room where the software over-predicted temperatures and residuals are lower when the software under-predicted temperatures. Table 8.46 shows the fitted roof space residuals at selected living room residuals for the three houses.

Table 8.46: Fitted values of roof space residuals at selected living room residuals for the three test houses

Living Room Residuals (ºC)	Roof Space Residuals (ºC) *		
	Slab Floor House	5-Star Timber Floor House	4-Star Timber Floor House
-6	-15.63	-17.51	-10.84
-4	-10.65	-13.16	-8.04
-2	-5.67	-8.81	-5.23
0	-0.69	-4.45	-2.42
+2	+4.29	-0.10	+0.38
+4	+9.27	+4.25	+3.19
+6	+14.25	+8.60	+5.98

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Residual values in the roof space of all three houses are generally significantly greater in magnitude than the residuals in the living room with the exception of the 4-star timber floor house, where the software's value of temperature under-prediction in the roof space was than less than in the living room. The magnitude of residuals in the roof space of the 4-star timber floor house is less than the magnitude of residuals in the roof space of the slab floor house and the 5-star timber floor house. Table 8.47 displays the fitted subfloor residuals at selected living room residuals for the 5-star and 4-star timber floor houses.

Table 8.47: Fitted values of subfloor residuals at selected living room residuals for the 5 and 4-star timber floor houses

Living Room Residuals (ºC)	Subfloor Residuals (ºC) *		
	Slab Floor House	5-Star Timber Floor House	4-Star Timber Floor House
-6	-	-5.70	-2.99
-4	-	-4.67	-2.15
-2	-	-3.63	-1.32
0	-	-2.60	-0.48
+2	-	-1.57	+0.35
+4	-	-0.54	+1.19
+6	-	+0.50	+2.03

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

The magnitude and direction of the subfloor residuals do not show a simular trend. Residual values in the subfloor of the 4-star and 5-star timber floor houses are smaller in magnitude than the residuals in the living room. This is particularly the case in the 4-star timber floor house. For instance, when the software over-predicted temperature in the living room by 6ºC, it over-predicted temperature in the subfloor by 2.99ºC and when the software under-predicted living room temperature by 2ºC, it under-predicted temperature in the subfloor by 0.35ºC. Table 8.48 shows the fitted residuals of bedroom 2 at selected bedroom 1 residuals for the three houses.

Table 8.48: Fitted values of bedroom 2 residuals at selected bedroom 1 residuals for the three test houses

Bedroom 1 Residuals (ºC)	Bedroom 2 Residuals (ºC) *		
	Slab Floor House	5-Star Timber Floor House	5-Star Timber Floor House
-6	-5.75	-4.13	-7.09
-4	-3.63	-2.49	-4.89
-2	-1.51	-0.86	-2.68
0	-0.62	+0.78	-0.48
2	+2.74	+2.42	+1.70
4	+4.86	+4.06	+3.93
6	+6.98	+5.69	+6.13

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Residual values for bedroom 2 of all houses are reasonably similar in magnitude and direction to the residuals in bedroom 1. Table 8.49 shows the fitted residuals of the roof space at selected bedroom 1 residuals for the three houses.

Table 8.49: Fitted values of roof space residuals at selected bedroom 1 residuals for the three test houses

Bedroom 1 Residuals (ºC)	Roof Space Residuals (ºC) *		
	Slab Floor House	5-Star Timber Floor House	4-Star Timber Floor House
-6	-21.62	-8.61	-12.09
-4	-13.34	-5.40	-8.52
-2	-5.07	-2.18	-4.94
0	+3.21	+1.03	-1.37
2	+11.48	+4.25	+2.21
4	+19.76	+7.46	+5.78
6	+28.03	+10.68	+9.36

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Fitted residual values in the roof space of the three houses are significantly greater in magnitude compared to the residuals of bedroom 1. This is particularly the case in the roof space of the slab floor house. For example, when the software over-predicted temperature in bedroom 1 by 6ºC, it over-predicted temperature in the roof space by 21.62ºC and when the software under-predicted temperature in bedroom 1 by 6ºC, it under-predicted temperature in the roof space by 28.03ºC. This strongly suggests that the roof space model needs to be investigated.

Table 8.50 displays the fitted residuals of the subfloor at selected bedroom 1 residuals for the 5-star and 4-star timber floor house.

Table 8.50: Fitted values subfloor residuals at selected bedroom 1 residuals for the timber floor houses

Bedroom 1 Residuals (ºC)	Subfloor Residuals (ºC) *		
	Slab Floor House	5-Star Timber Floor House	4-Star Timber Floor House
-6	-	-3.52	-5.54
-4	-	-2.77	-4.58
-2	-	-2.03	-3.62
0	-	-1.28	-2.67
+2	-	-0.54	-1.71
+4	-	+0.21	-0.75
+6	-	+0.95	+0.21

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

The direction of subfloor residuals in the timber houses is generally similar except for the bedroom 1 residual of 4ºC and 6ºC. Subfloor residuals in the 4-star and 5-star timber floor house are smaller in magnitude compared to the residuals in bedroom 1. The magnitude of negative residuals (over-predicting temperature) in the subfloor of the 4-star timber floor is closer to residual values of bedroom 1 compared to that of the 5-star timber floor house.

d) Correlation of Living Room and Bedroom 1 Residuals and Climate Parameters

1) Correlation of Living Room Residuals and External Air Temperatures

The fitted values of the living room residuals at selected external air temperature for the three houses are shown in Table 8.51.

Table 8.51: Fitted values of living room residuals at selected external air temperatures of the three test houses

External Temperature (ºC)	Living Room Residuals (ºC) *		
	Slab Floor House	5-Star Timber Floor House	4-Star Timber Floor House
2	+2.04	+6.55	+6.68
6	+1.50	+4.90	+4.96
10	+0.96	+3.25	+3.04
14	+0.42	+1.65	+1.14
18	-0.13	-0.04	-0.76
22	-0.67	-1.69	-3.69
26	-1.21	-3.34	-4.57

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Table 8.51 shows that at the external temperature of 2ºC to 26ºC the residuals in the living room of the slab floor house display the smallest magnitude. The direction of residuals is similar in all three houses. At the external temperature of 18ºC the residuals in the living room are smallest in all three houses. At the external temperature of 2ºC to 14ºC the software under-predicted temperatures and at the external temperature above 18ºC the software over-predicted temperatures in the living room of all three test houses. The magnitude of positive residuals is greater than negative residuals in the living room of all three houses.

2) Correlation of Bedroom 1 Residuals and External Air Temperatures

The fitted values of bedroom 1 residuals at selected external air temperatures for the three houses are shown in Table 8.52.

Table 8.52: Fitted values of bedroom 1 residuals at selected external air temperature of the three test houses

External Temperature (ºC)	Bedroom 1 Residuals (ºC) *		
	Slab Floor House	5-Star Timber Floor House	4-Star Timber Floor House
2	+0.70	+5.66	+5.35
6	+0.22	+3.34	+3.62
10	-0.26	+1.02	+1.89
14	-0.74	-1.29	+0.16
18	-1.21	-3.61	-1.56
22	-1.69	-5.92	-3.29
26	-2.17	-8.24	-5.02

*Note: Positive values indicate an under-prediction and negative values indicate an over-prediction of temperature

Table 8.52 shows that at the external temperature of 2ºC to 26ºC, the magnitude of residuals in bedroom 1 of the slab floor house is significantly smaller than the residuals in bedroom 1 of the timber floor houses. An examination of the dataset shows that at the external temperature of 8ºC residuals are smallest in bedroom 1 of the slab floor house; at 12ºC residuals are smallest in bedroom 1 of the 5-star timber floor house; and at 14.5ºC residuals are smallest in bedroom 1 of the 4-star timber floor house.

e) External Air Temperature and the Software's Change of Simulation Direction

Table 8.53 shows when the software changed prediction direction from under to over-predicting temperatures in the living room and bedroom 1 of the three houses.

Table 8.53: Calculated external air temperatures when the software changed prediction direction from under to over-predicting temperatures in the living room and bedroom 1 of the test houses

Zones	External Air Temperature (ºC) when the Software changed Prediction Direction (below indicated temperatures the software under-predicted room temperature, above indicated temperature the software over-predicted room temperature)
Living Room Slab Floor House	17.06
Living Room 5-Star Timber Floor House	17.90
Living Room 4-Star Timber Floor House	16.40
Bedroom 1 Slab Floor House	7.84
Bedroom 1 5-Star Timber Floor House	11.77
Bedroom 1 4-Star Timber Floor House	14.39

The external temperatures at which the software changes from under to over-prediction are similar in the living room of the three houses, that is, it ranges from 16.40ºC in the 4-star house, 17.06ºC in the slab floor house to 17.90ºC in the 5-star timber floor house. On the other hand, the external temperature at which the software changes direction, (from under to over-prediction of temperatures) is dissimilar in bedroom 1 of the test houses, that is, it ranges from 7.84º C in the slab floor house to 14.39ºC in the 4-star timber floor house. The critical temperature when the software changes simulation direction, (from under to over-predicting) is significantly lower in bedroom 1 of the test houses (7.84ºC to 14.39ºC) than in the living room of the houses (16.40ºC to 19.90ºC).

f) Correlation of Living Room and Bedroom 1 Residuals and Global Solar Radiation, Wind Speed and Wind Direction

Correlation of living room and bedroom 1 residuals and global solar radiation, wind speed and wind direction are very weak indicating that global solar radiation, wind speed and wind direction had no direct influence on the living room and bedroom 1 residuals.

8.5. Summary of Statistical Analysis

The statistical correlation of measured and simulated temperature shows the following results:

1. The correlation of data between the simulated and measured temperatures in the living room and bedroom 1 is high for all houses. r^2 values are greater in the living room and bedroom 1 of the slab floor house then in the 5-star and 4-star timber floor houses;

2. The high correlation of measured versus simulated temperatures in the test houses suggests that the fundamental simulation engine works well, basically agreeing with the temperature trends of the measured values;

3. Individual hourly simulated temperatures do not match with the measured values and are at times rather dissimilar;

4. Based on fitted values the difference of measured and simulated temperatures are significantly smaller in the living room and bedroom 1 of the slab floor house, than in the 5-star and 4-star timber floor houses;

5. Based on fitted values differences of measured and simulated temperatures are greatest in bedroom 1 of the 4-star timber floor house, where the software under-predicted room temperature by 5.40ºC in the living room and by 7.41ºC in bedroom 1, at the measured temperature of 10ºC;

6. Temperature differences between measured and simulated values are greater at lower room temperatures of 10ºC to 14ºC in the living room and bedroom 1 of all the test houses. At higher room temperatures of 26ºC to 30ºC the temperature differences between measured and simulated values are smaller in the living room. At room temperatures of 16ºC to 20ºC residuals are smaller in bedroom 1 of the houses as compared to lower room temperatures. The only exception to this trend occurs in bedroom 1 of the slab floor house, where the temperature difference between measured and simulated temperature is greatest at the higher room temperature of 20ºC.

7. Scatterplots for the roof space of all three houses show concentrated data around the best-of-fit line between temperatures of 5ºC and 20ºC (Appendix 4). However, over 20ºC the data becomes significantly more scattered and this suggests, that the software does not correctly simulate roof temperatures over 20ºC.

The histogram analysis revealed the following trends:

1. The software under-predicted temperatures for most of the time in the living room, bedroom 1 (with the exception of bedroom 1 in the slab floor house), and in the roof space of all houses. In bedroom 1 of the slab floor house the software mostly over-predicted temperature 69% of the time. The software also over-predicted temperatures in the subfloor of the 4-star and 5-star timber houses, 82.5% of the time in the 5-star timber floor house and 97.2% of the time in the 4-star timber floor house. The overwhelming proportion of time that the software over-predicted temperature in the subfloor of the timber floor houses suggests that the subfloor model needs to be investigated;

2. The actual maximum amount of over- and under-prediction of temperatures in the test houses is excessive in some cases. This is particularly prevalent in the roof space of all three houses. For instance, the software over-predicted temperature in the roof space of the 4-star timber floor house by up to 19.8ºC and under-predicted temperature by up to 10.52ºC. This suggests that the roof space model needs to be investigated.

The comparison of temperature residuals of adjoining zones shows the following characteristics:

1. The correlation ratios range from moderate to high. Correlation ratios are high only for bedroom 1 versus bedroom 2 residuals for all houses;

2. The magnitude of roof space residuals are significantly greater in the living room and bedroom 1 residuals of all houses;

3. The magnitude of subfloor residuals are smaller than the living room and bedroom 1 residuals of the timber floor houses;

4. Scatterplots of room residuals versus adjoining zone residuals show that the software mostly overestimated subfloor temperatures in the timber floor houses.

The examination of the correlations of room residuals (living room and bedroom 1) versus the climate parameters, namely: external air temperature, global solar radiation, wind speed and wind direction are summarised as follows:

1. All room residuals versus climate parameters had a negative linear correlation, with correlation ratios ranging from: moderate with external air temperature, and weak for the correlation with the remaining climate parameters of global solar radiation, wind speed and wind direction;

2. When the room residuals are compared with the external air temperature, the room residuals are significantly smaller in the slab floor house than the 5-star and 4-star timber floor houses;

3. Living room residuals are smallest at the external air temperature of 16.40ºC to 17.90ºC for all three test houses;

4. At an external temperature of 7.8ºC, residuals are smallest in the slab floor house; at an external temperature of 11.7ºC residuals are smallest in the 5-star timber floor house and at an external temperature of 14.3ºC residuals are smallest in the 4-star timber floor house;

5. Room residuals in all three test houses are greater at lower room temperatures of 2ºC to 6ºC, and room residuals in all three houses are lower at higher room temperatures of 18ºC to 22ºC;

6. The critical external air temperatures at which the software changes direction, (from under to over-prediction) are similar in the living room of the three houses, but dissimilar in bedroom 1 of the test houses;

7. As correlation of room residuals versus global solar radiation, wind speed and wind direction is weak; this suggests that these climate parameters had no effect on the living room and bedroom 1 residuals.

A summary of test results and the conclusion of this research, including recommendations for further research will be discussed in Chapter 9.

Chapter 9: Conclusions and Recommendations

9.1. Overview

This research study focused on the empirical validation of the HERS AccuRate software by comparing the measured temperatures with simulated temperatures of three test houses in Kingston, Tasmania. The research sought to address concerns about accuracy of the star rating of this software.

Empirical thermal performance data was gathered from three purpose-built light-weight test houses from 5 September to 26 September 2007 for the purpose of validating the NatHERS software, AccuRate, in cool temperate climates. The research methods used in this project were linked closely to two previous case studies, namely: the three heavy-weight test cells in Newcastle, NSW, and the three light-weight test cells in Launceston, Tasmania.

The test houses were constructed in Kingston, Hobart with the same quality and workmanship, in accordance with the general building standards for residential buildings in Australia. The test houses were designed to meet target star-ratings as follows:

- A 4-star house with an enclosed perimeter timber floor;
- A 5-star house with an enclosed perimeter timber floor;
- A 5-star house with a concrete slab floor house.

An extensive array of monitoring equipment was installed in the three test houses including an on-site weather station situated on the roof of the test houses. Utmost care was taken to ensure the proper installation of cables and sensors, including the testing of wiring and an elaborate checking of calibration to ensure the proper functioning of the test houses' monitoring systems. Validation comparison showed similar temperatures trends for all three houses, indicating that instrumentation and sensors provided reliable data.

The empirical data were subjected to a thorough and meticulous checking and cleaning process that resulted in a high quality data set for the empirical validation. The thermal performance of the three houses was simulated using AccuRate, based on the 'as-built' and 'on-site climate' data sets. AccuRate simulated hourly temperatures in various zones of the houses were compared to measured temperatures using graphical and statistical methods.

The test houses computer models were subject to extensive envelope simulations providing predicted temperatures. These models included a range of changes to the software's input parameters including changes of construction details, infiltration rates and climate data. On-site climate data was used instead of the AccuRate's in-built TMY climate file. The houses were simulated in a free-running condition, they were unoccupied and unconditioned. Validation comparison showed similar temperature trends for all three houses, indicating that instrumentation and sensors provided reliable data.

Simulated temperatures of the test houses were compared with measured temperatures showing that simulated temperature profiles fundamentally matched the measured temperature profiles. The measured temperature profiles were generally closer to the simulated profiles in the concrete slab floor house than in the two timber floor houses. With the exception of the living room of the slab floor house, simulated temperature were quite dissimilar to measured temperatures, and this was especially the case in the hallway and roof space of all houses and in the subfloor of the timber floor houses.

This research showed that an aspect of precise software envelope simulation depends on accurate climate data. However, this study demonstrated clearly that the external data input representing the climate is not appropriately accounted for by the AccuRate software and indeed showed significant differences between site-measured and in-built TMY climate inputs. The analysis showed that maximum site measured temperatures were up to 14.4ºC higher and the minimum temperatures up to 4ºC lower compared to AccuRate's in-built TMY temperature data. Differences in global solar radiation of up to 459W/m² between site measured and in-built TMY data were also recorded. Accurate software simulation can not be expected with these large differences of climate data consequently validations undertaken using AccuRate's in-built TMY data files are likely to result in meaningless validations.

The research hypothesis is that AccuRate's predictions are similar to measured temperature values. This study demonstrated that, although the measured and predicted temperature profiles were at times close, the AccuRate predicted individual temperatures were however dissimilar and at times, significantly higher than the measured values. This was especially the case in the roof space and the hallway of all three test houses.

Even with the use of site measured climate data and a range of modification to the construction input data so the software more closely represented the as-built construction condition, comparison between simulated and measured temperatures were mostly dissimilar and at times, very dissimilar. It was only in the living room of the slab floor house where simulated and measured temperatures were close enough, expected from such a software program.

The overwhelming dissimilarity of temperature comparison between simulated and measured temperatures in the hallway and the roof space of all houses and in the subfloor of the timber floor houses leads to the conclusion the prediction of the cooling and heating load, and the star rating of this program is seriously compromised. Inaccurate star rating reports may in fact influence many residential building approvals by not achieving the increased energy efficiency in the homes and at the same time, not reducing the required greenhouse gas emission.

9.2. Conclusions

The graphical and statistical analyses showed that simulated and measured temperatures had comparable temperature profiles for most zones of the houses, but individual hourly simulated temperatures did not correspond with the measured temperature values, and were at times, quite dissimilar. Both the graphical and the statistical analyses showed that simulated temperatures were closest to measured values in the living room and bedroom 1 of the slab floor house, and simulated temperatures diverged most strongly from measured values in the hallways and roof spaces of all three test houses.

The AccuRate room temperature predictions were closer to the measured temperatures in the concrete slab floor house compared to the enclosed subfloor timber floor houses. This trend was also observed when the correlation of room residuals was compared with the external air temperatures, where the residuals for the living rooms and bedrooms 1 of the timber floor houses were significantly higher than the residuals in the living room and bedroom 1 in the slab floor house.

For most of the time, AccuRate over-predicted temperatures in the subfloor of the timber floor houses. When statistically fitted simulated temperatures were compared to measured temperatures in the subfloor of the timber floor houses, the coefficient of determination were very high (0.9583 for the 5-star timber house and 0.9339 for the 4-star timber house). Comparison of fitted simulation temperatures with the measured temperatures in the subfloor also showed that AccuRate predominantly over-predicted temperatures at measured temperature values of 8ºC to 18ºC (Appendix 4).

Relative to the slab floor house, the predicted room temperatures of the timber floor houses were in general significantly higher than measured temperatures. The high correlation coefficient of residuals between the rooms and the subfloor could imply that simulation errors in the subfloor may have caused the notably higher room residuals in the living room and bedroom 1 of the timber floor houses, compared to the much lower residuals in the living room and bedroom 1 of the slab floor house. This suggests that AccuRate's subfloor model needs to be investigated as a priority, before examining other aspects of the software.

Compared to other zones, the range of simulated temperatures was significantly wider in the hallway of all three houses. However, simulated temperatures were significantly closer to measured values in the hallway of the slab floor house than in the hallway of the timber floor houses. This observation suggests that simulated temperature errors in the subfloor of the timber houses are also most likely affecting temperature errors in the hallway, as in all rooms of the timber floor houses. This trend is also observed in bedroom 1 of the timber floor houses, where simulated temperatures diverged most strongly from measured values than the hallway of the slab floor house. Again, this suggests that AccuRate's subfloor model needs to be further investigated.

The range of simulated temperatures in the roof space of all three houses was always wider than the range of measured values. For example, at temperatures over 20ºC, AccuRate over-estimated temperatures by up to 19.8ºC in the roof space of the 4-star timber floor house (Appendix 4). The significant amount of over-prediction in the roof space of all three houses must also have a direct influence on the residuals of the room zones, as they are thermally connected. This trend was observed in the rooms of the houses where residuals were higher at room temperatures above 20ºC. The significant amount of over-prediction in the roof space could suggest that AccuRate might not be correctly modeling the effect of solar radiation in these spaces. Hence, the roof space model needs to be investigated further. If globe temperatures were used in the roof space rather than air temperatures, simulated temperatures might have been considerably closer to measured values as the globe thermometer would have been able to better to measure the mean radiant temperatures of the black roof, especially during warm, sunny days. However, no globe thermometers were installed in the roof spaces of the test houses.

At the time this research was undertaken, the software did not provide alternative values for framing factors. Instead of using the default wall and ceiling insulation setting, the as-built framing factors for the external walls and ceiling of all three houses were manually calculated;

then the modified values for walls and ceiling were used for the AccuRate simulations. As a result, the actual framing factors reduced the average thermal resistance of the walls by 36%.

It must be mentioned that houses were monitored in a free-running operation, that is, with no additional heating or cooling input. However, if the houses were heated, the reduced level of insulation in the walls and ceiling would have further increased the differences between simulated and measured temperatures, and consequently, heating and cooling requirements. The omission of the framing ratio as a fabric input for the envelope simulation of AccuRate disregards the realities of current standard design and construction practices. It must be noted, however, that the CSIRO's latest version 'AccuRate sustainability' now has the capability of considering the thermal bridging; however at this stage, it has not yet been released by the NatHERS administrator (CSIRO; D Chen 2011, pers. comm., 5 March).

AccuRate's predictions using the in-built TMY climate data were compared with AccuRate simulations, using site-measured climate data. Based on the in-built TMY data, the simulated temperatures in the living room of the slab floor house were significantly different, compared to AccuRate's simulation with the site-measured climate data. This suggests that AccuRate's in-built climate data needs to be examined and possibly upgraded to provide more realistic climate parameters.

As the houses were simulated in a non-star rating mode (that is in free-running condition), the comparative performance of the homes relative to the star rating were not investigated in this project. However, AccuRate's significant over-prediction of subfloor and roof temperatures must have subdued the effects of the building features that satisfy the star rating for the houses. AccuRate's over-prediction of the subfloor temperature must also have affected AccuRate's room simulation temperature, which would result in higher cooling load requirements and lower star ratings, compared to the slab floor houses. These circumstances will particularly affect timber floor houses in warmer climate zones of Australia. The inaccurate representation of star rating compliant timber floors can have significant ramifications for home owners and the building industry. Achieving the required star rating for timber floor houses might require additional thermal performance measures compared to slab floor houses, resulting in increased and unwarranted construction costs.

Examination of AccuRate's subfloor and roof models are highly recommended, so that the star ratings for both timber and slab floor houses are more realistic, eventually providing the users of the software with the confidence that AccuRate star rating predictions are indeed accurate.

The question of the expectance of software's simulation accuracy must be also addressed. The degree of a software accuracy deemed to be satisfactory must be determined by the user before validating the program. Mahajan (1984) pre-nominated an uncertainty band of ±0.5ºC in a comparison of measured and predicted air temperatures for the NIST passive solar test facility at Gaitherburg, Maryland, USA. All simulation predictions of more or less than 0.5ºC would fail the validation test and would be deemed as unsatisfactory. Applying Mahajan's uncertainty band to the accuracy of simulated temperatures by HERS AccuRate, all simulation prediction would be deemed as unsatisfactory. Eppel & Lomas (1992) stated that the simulated maximum temperature of software HTB 2 was 2.9ºC lower than the measured temperature in a comparison of measured and predicted air temperature for the NIST passive solar test facility at Maryland, and this could be still classified as a good prediction. Even with a wider uncertainty band of 2ºC - 3ºC, AccuRate simulation predictions would only be deemed as satisfactory in the living area and bedrooms of the slab floor house while in all other zones of the houses, AccuRate predictions would have been deemed as unsatisfactory.

The considerable disagreement of temperatures between simulated and measured values will significantly compromise the accuracy of the heating and cooling loads and consequently, the star rating of the software.

9.3. Recommendation for further Research

This research project covered 21 days of empirical validation from, 5 September to 26 September 2007. Longer periods of validation are recommended so that the validation process covers a wider variation of climate variables. The following areas need further investigation:

- The software significantly over-estimated residuals in the subfloor of the 5-star and 4-star timber floor houses. Further work to improve the subfloor model should be undertaken before any other research is carried out;

- The greatest residual values were recorded in the roof spaces of the three houses. The reasons for the large residuals in the roof spaces have not yet been established and further detailed measurements and thermal modeling is required to determine the source of errors and hence, the accuracy of temperature predictions in the roof space;

- Temperature profiles were quite dissimilar in the hallway of the three test houses. The causes of the large differences between the simulated and measured temperature profiles has not yet been determined and further detailed investigation of the modeling of the hallway zone is required;

- The analysis shows that residuals were significantly greater at room temperatures of 10ºC to 14ºC in the living room and bedroom 1 than at temperatures above 14ºC in the three houses. This gives the impression that the software has its least capacity to simulate temperatures at lower room temperatures, particularly between 10ºC to 14ºC, and this trend should be further investigated;

- Due to time limitations in this project, only the thermal performance of the living room and bedroom 1 of the houses were fully analysed. Therefore the thermal performance of remaining zones of the houses should also be fully investigated, to confirm already established simulation trends and determine other likely causes of simulation errors of the software;

- As many as 68 sensors were installed in each house, mainly measuring air temperature. For this project, the data of only 24 temperature sensors were analysed. The data from the remaining sensors may shed light and answer questions raised;

- This research has been limited to a cool moderate climate only, however, the empirical validation of AccuRate also needs to be tested for other climates, particularly in a warm humid climate;

- The empirical validation for this project included only the comparison of simulated and measured temperatures of the houses in free-running operation. If the houses were to be assessed in a star rating mode (that is conditioned), the star rating and heating and cooling requirements of AccuRate's standard model could be compared with AccuRate's empirical validation model, which includes changes to the as-built construction and the use of site-climate data. This type of comparison would then provide a quantitative validation of the three test houses.

The data for this research project were recorded with the houses in free-running operation. However, the houses were also monitored in an occupied state for a further three years and a significant amount of additional data has already been collected. Areas of further research could include the following suggestions:

- The monitoring of heating and cooling energy, to extend the validation of the software by comparing simulated and measured values over a minimum period of one year;

- The further validation of the software comparing building envelope simulation with measured values in an occupied stage of the houses for a minimum period of one year. This would then include all characteristics of the site-climate and would clearly distinguish the accuracy of winter and summer simulation performance of the software;

- The collection of ground and sub-ground temperature data of the three houses for a minimum period of one year. These data would be useful for any further research, particularly in relation to the improvement of the subfloor model for enclosed perimeter timber floor houses;

- The comparison of thermal performance of the 5-star timber floor house with the concrete slab floor house. The concrete slab floor house is identical to the 5-star timber floor house, but uses a 100mm concrete slab floor in lieu of the timber floor construction. The effect of the thermal mass of the concrete slab floor on thermal performance could be analysed and compared to the thermal performance of the house with the timber floor construction. This study would enhance the understanding of the use of thermal mass in residential buildings. The test houses are situated in a climate zone (cool temperate) with a large diurnal temperature swing, where the proper use of thermal mass can significantly lower heating and cooling loads of buildings.

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Appendices

Appendix1

Photographic Documentation of the Installation of Measuring Equipment

Figure A1.1: Preparing the hole for the installation of temperature sensor 1m below ground level

Figure A1.1: Installing the pipe for cabling the sensor below ground level

Figure A1.3: Installing the cable for the sensor below ground level

Figure A1.4: Drilling a large hole through the foundation perimeter wall for the cable connection to the data logger in the meter box

Figure A1.5: Installing the underground temperature sensor

Figure A1.6: Installing the temperature sensors for measuring the temperatures through a wall section

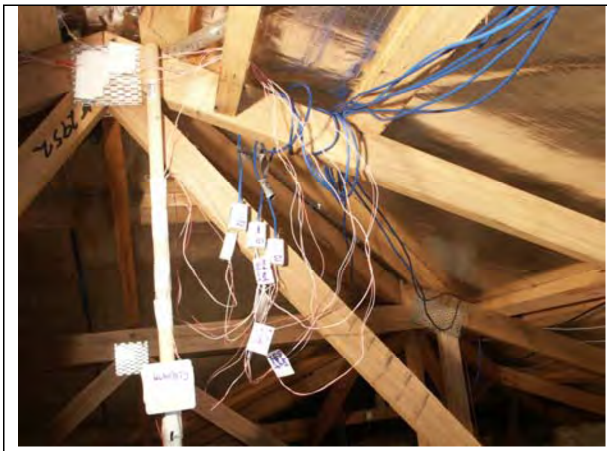

Figure A1.7: Installing the Krone connectors, sensors and cables in the ceiling space

Figure A1.8: Installing the globe thermometer in the garage

Figure A1.9: Tracer gas cart during the tracer gas testing to establish the air change rates in the houses

Figure A1.10: Installation of the Solar pyranometer at the wall of the houses

Figure A1.11: Installation of the current sensors

Figure A1.12: Installation of the data logger

Figure A1.13: Installation of temperature sensor to measure the ceiling surface temperature

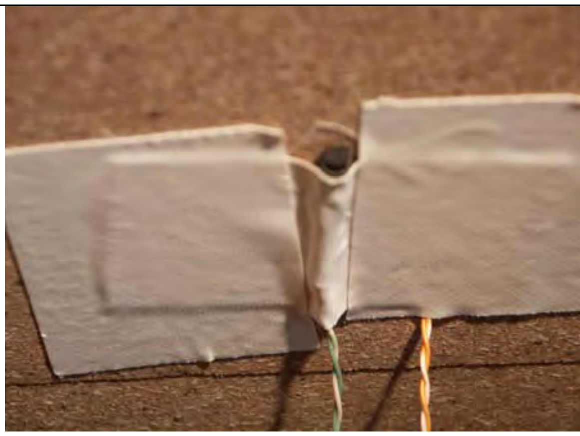

Figure A1.14: Installation of temperature sensor to measure the surface temperature underside of the timber floor

Figure A1.15: Installation of temperature sensors to measure the ground temperature

Figure A1:16: Installation of temperature sensor to measured the surface temperature of the external side of sarking

Figure A1.17: Installation of temperature sensor to measure the air temperature at the centre of the living room

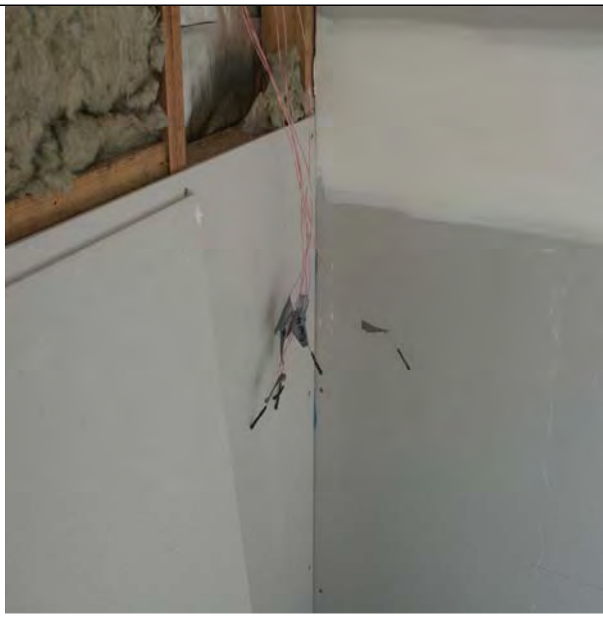

Figure A1.18: Installation of temperature sensors to measure the temperatures through the various section of the brick veneer wall

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Appendix 3

Simulated and Measured Temperatures for Bedroom 2, Bathroom and Garage for the Test Houses

1) Slab Floor House

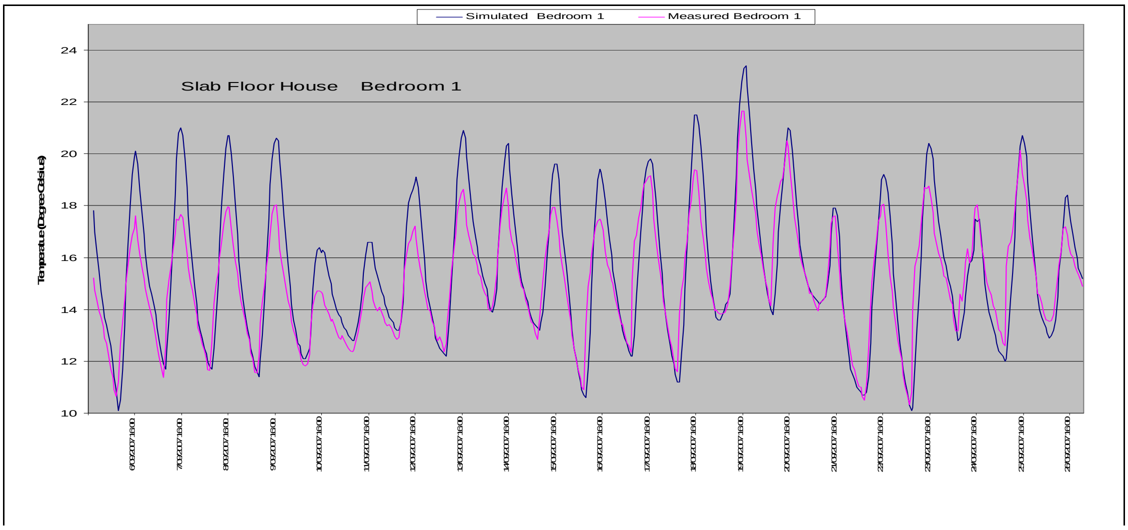

Figure A3.1: Simulated and measured temperature in bedroom 2 of the slab floor house

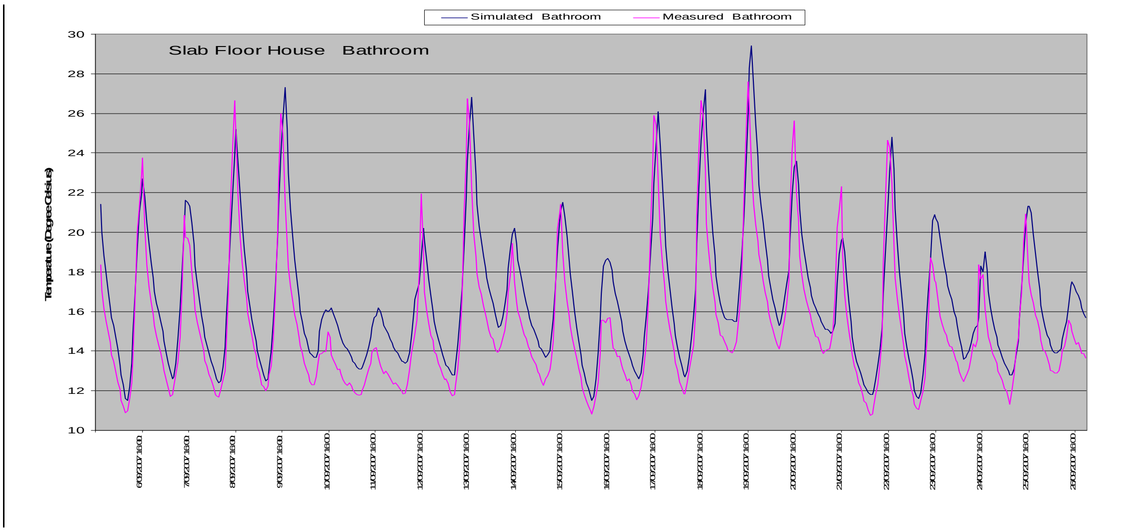

Figure A3.2: Simulated and measured temperature in bathroom of the slab floor house

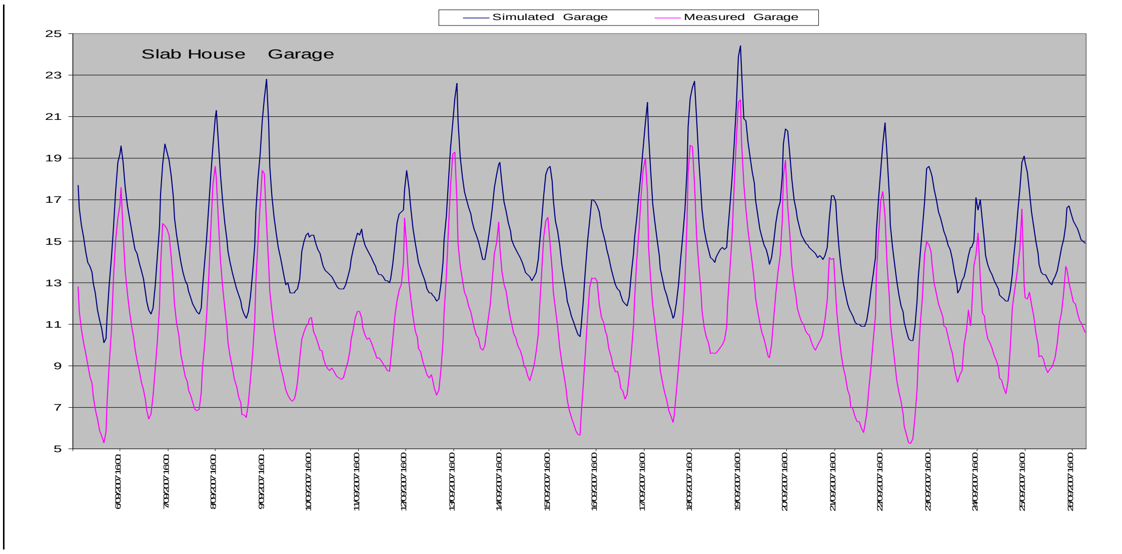

Figure A3.3: Simulated and measured temperature in the garage of the slab floor house

2) 5-Star Timber Floor House

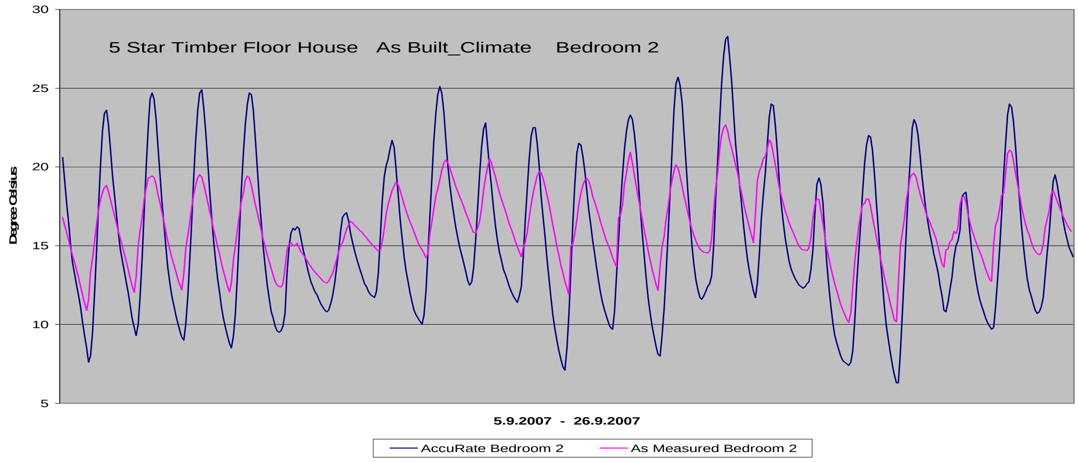

Figure A3.4: Simulated and measured temperature in bedroom 2 of the 5-star timber floor house

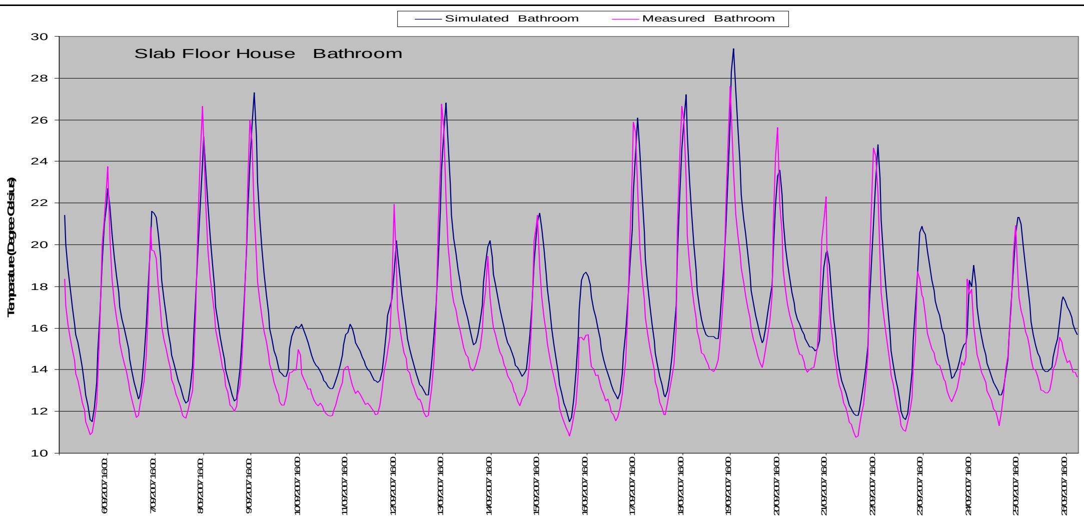

Figure A3.5: Simulated and measured temperature in the bathroom of the 5-star timber floor house

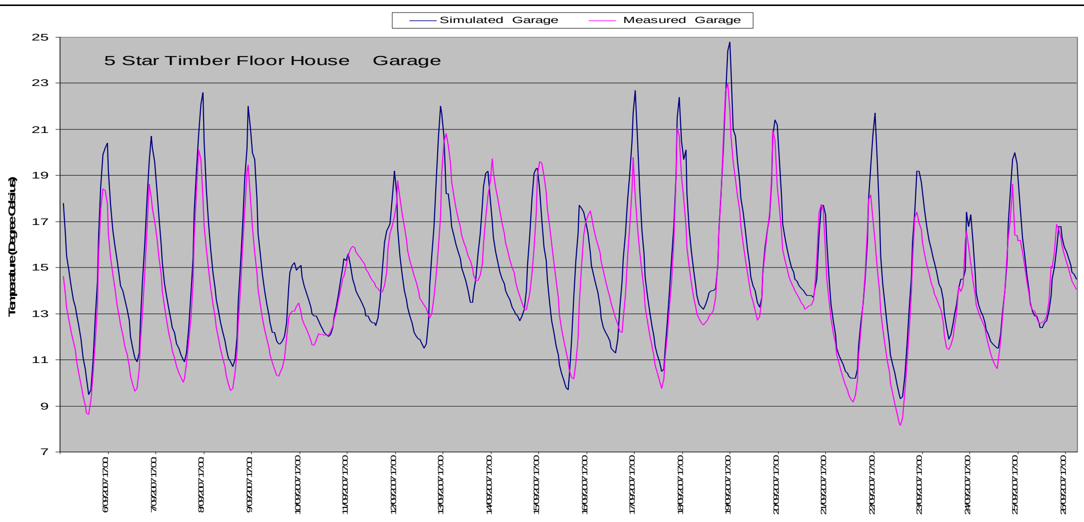

Figure A3.6: Simulated and measured temperature in the garage of the 5-star timber floor house

3) 4-Star Timber Floor House

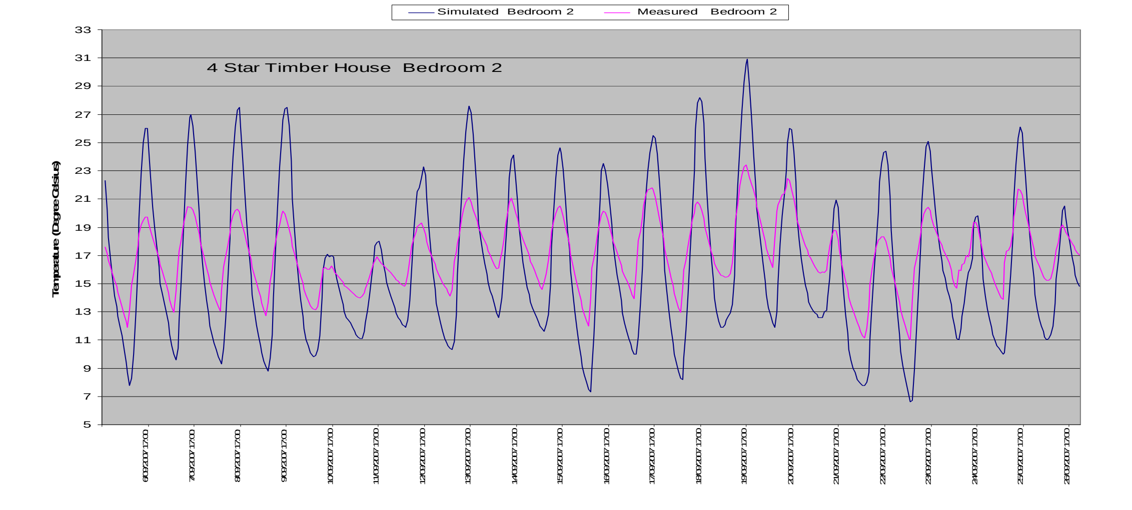

Figure A3.7: Simulated and measured temperature in bedroom 2 of the 4-star timber floor house

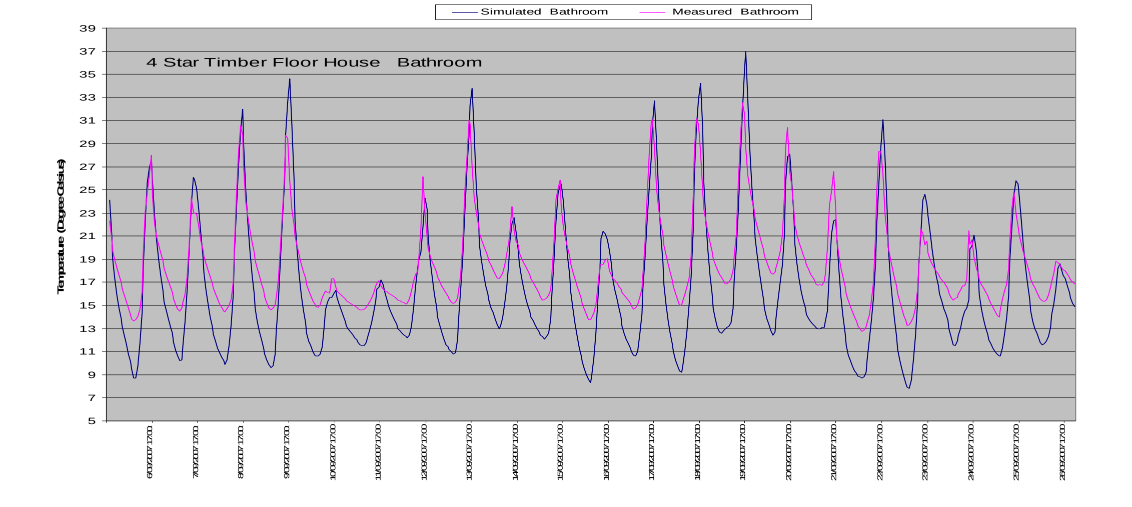

Figure A3.8: Simulated and measured temperature in the bathroom of the 4-star timber floor house

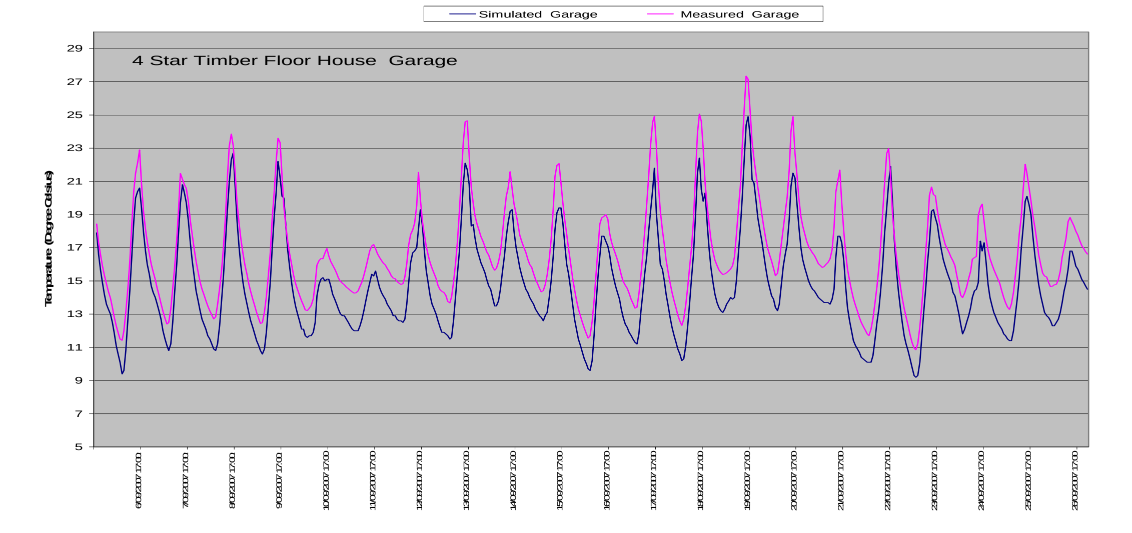

Figure A3.9: Simulated and measured temperature in the garage of the 4-star timber floor house

Appendix 4

<u>Statistical Scatterplots, Residual Histograms and Fitted Temperature Values for other House Zones</u>

1) Slab Floor House

Correlation between Measured and Simulated Temperatures for the Slab Floor House

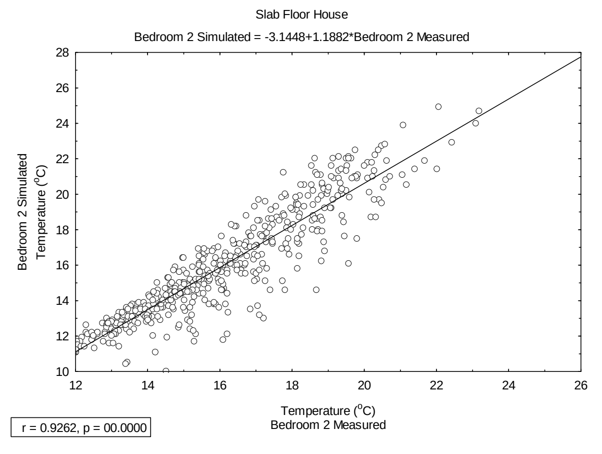

Figure A4.1: Correlation between simulated and measured temperature for bedroom 2

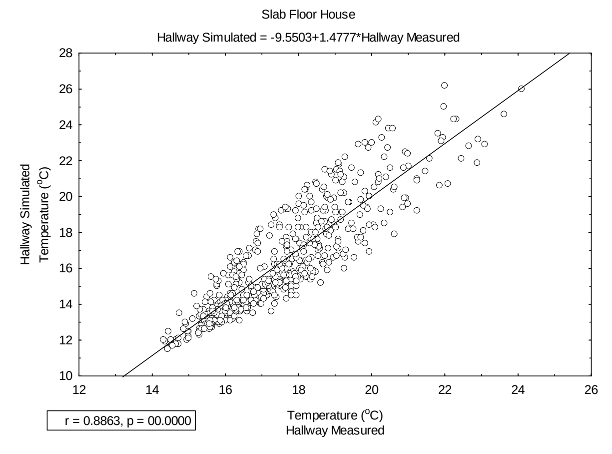

Figure A4.2: Correlation between simulated and measured temperature for the hallway

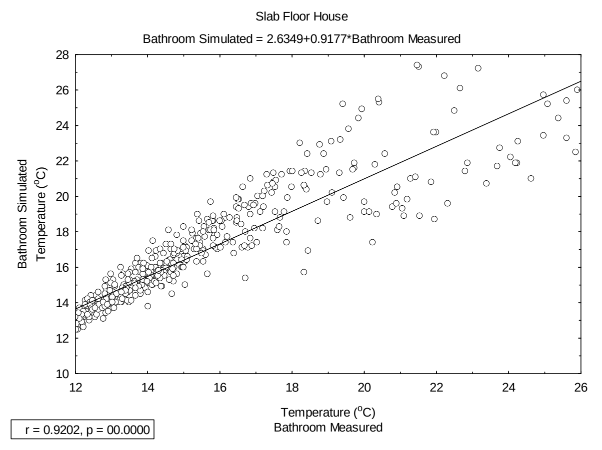

Figure A4.3: Correlation between simulated and measured temperature for the bathroom

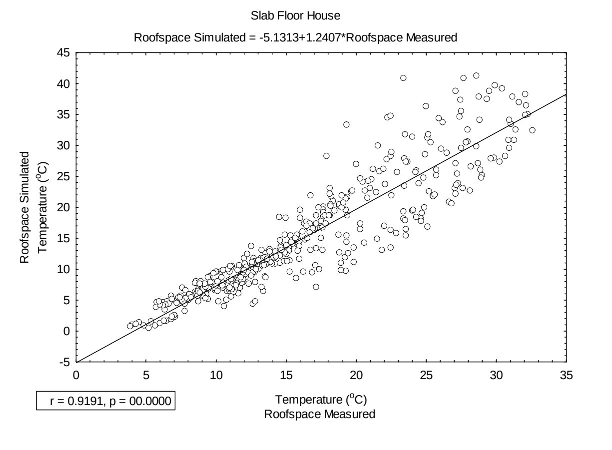

Figure A4.4: Correlation between simulated and measured temperature for the roof space

Residual Histograms for the Slab Floor House

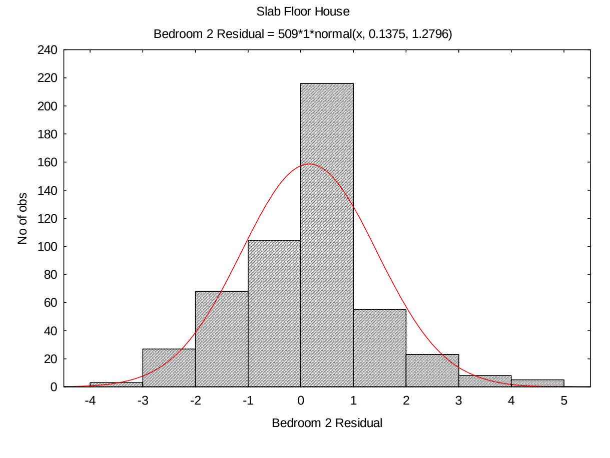

Figure A4.5: Distribution of residuals in bedroom 2

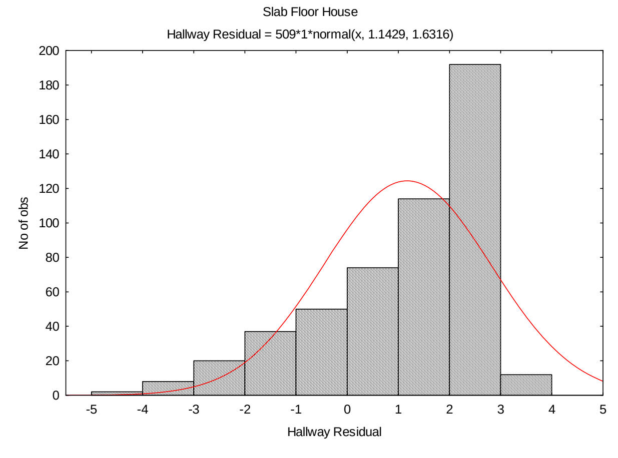

Figure A4.6: Distribution of residuals in the hallway 2

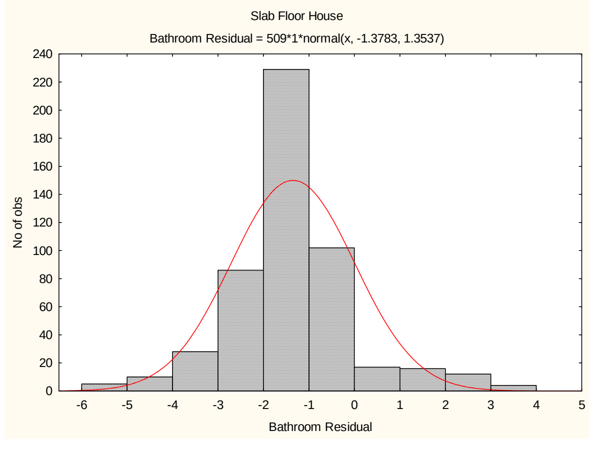

Figure A4.7: Distribution of residuals in the bathroom

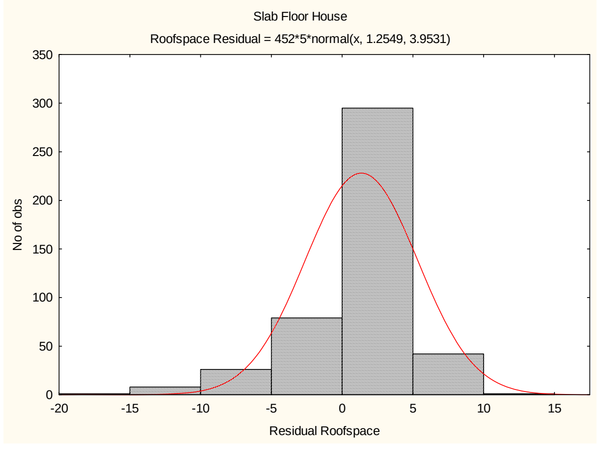

Figure A4.8: Distribution of residuals in the roof space

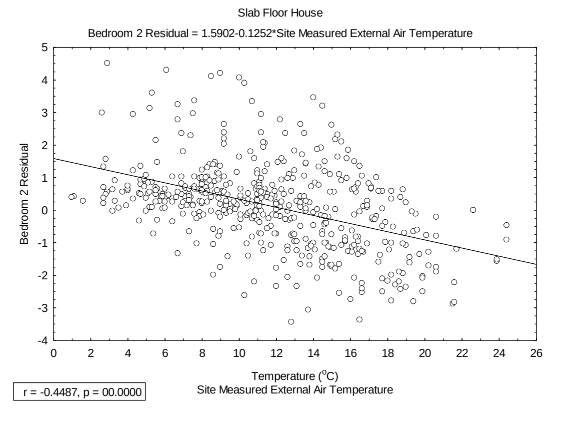

Figure A4.9: Correlation between bedroom 2 residuals and external air temperature

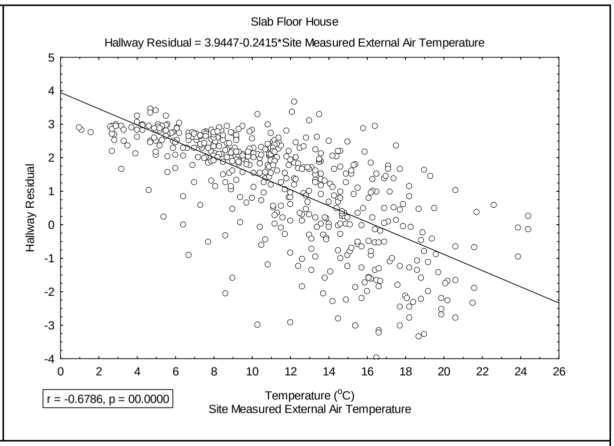

Figure A4.10: Correlation between hallway residuals and external air temperature

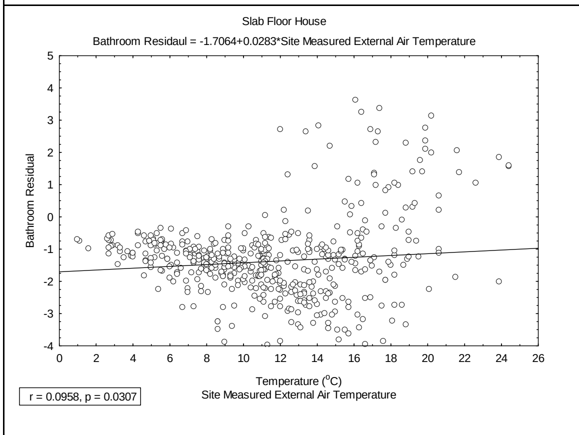

Figure A4.11: Correlation between bathroom residuals and external air temperature

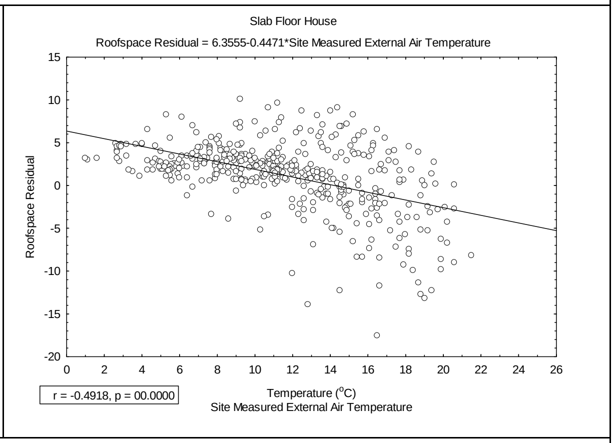

Figure A4.12: Correlation between roof space residuals and external air temperature

2) 5-Star Timber Floor House

Correlation between Measured and Simulated Temperatures for the 5-Star Timber Floor House

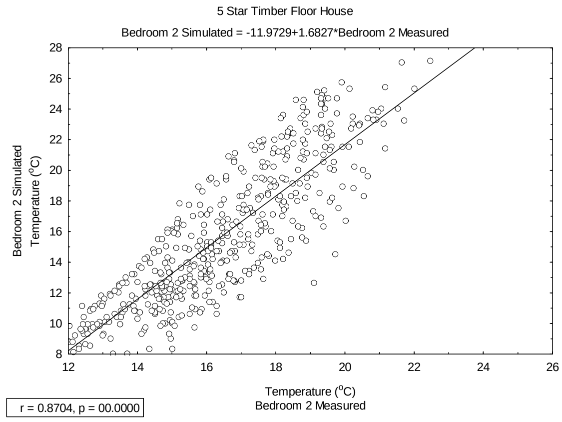

Figure A4.13: Correlation between simulated and measured temperature for bedroom 2

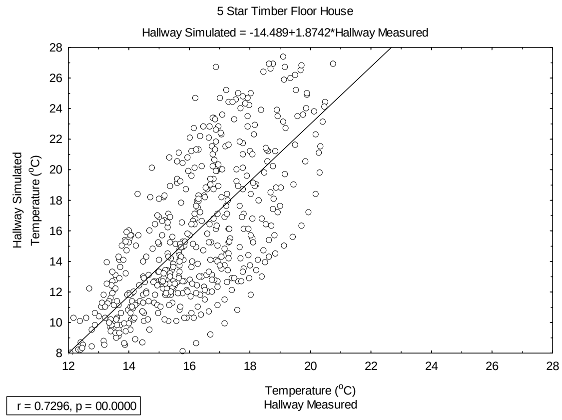

Figure A4.14: Correlation between simulated and measured temperature for the hallway

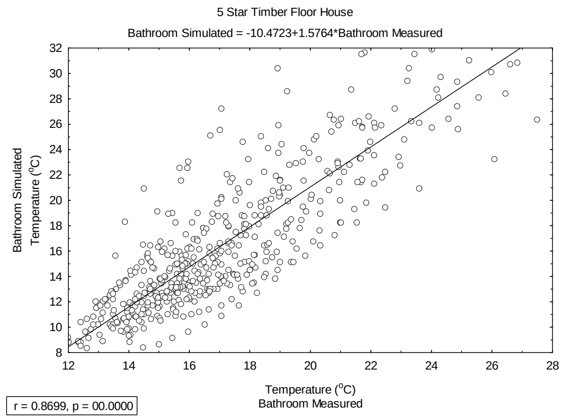

Figure A4.15: Correlation between simulated and measured temperature for the bathroom

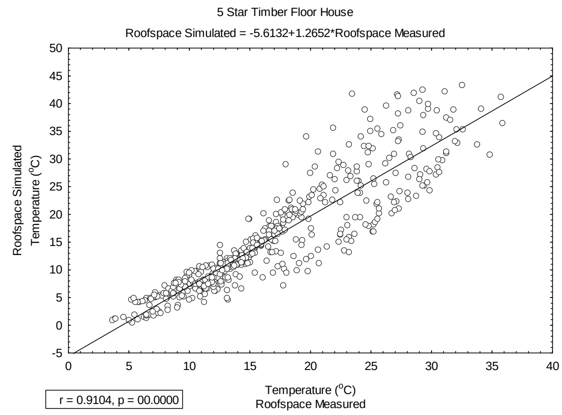

Figure A4.16: Correlation between simulated and measured temperature for the roof space

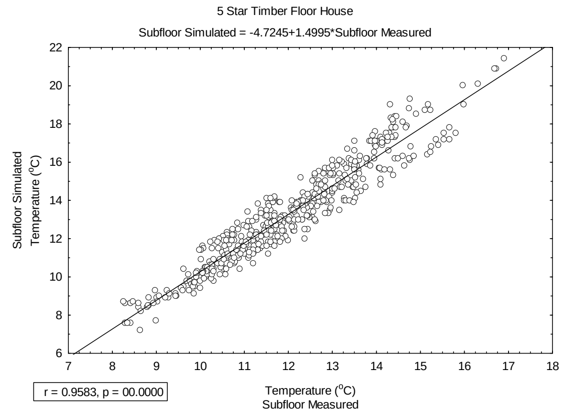

Figure A4.17: Correlation between simulated and measured temperature for the subfloor

Residuals Histograms for the 5-Star Timber Floor House

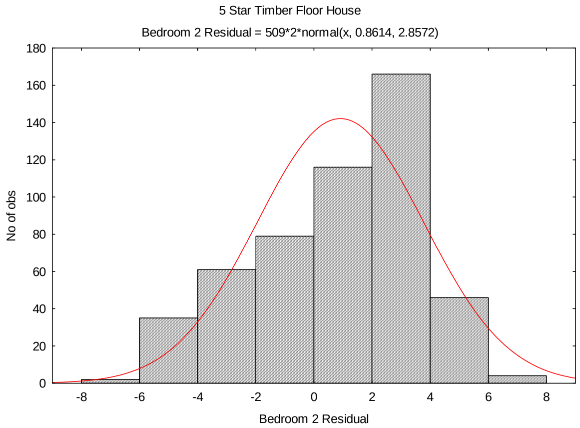

Figure A4.18: Distribution of residuals in bedroom 2

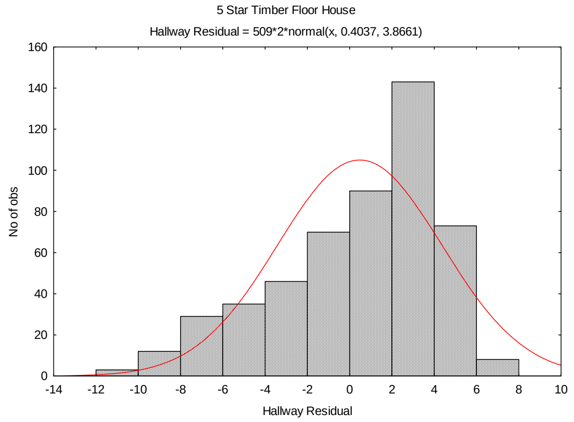

Figure A4.19: Distribution of residuals in the hallway

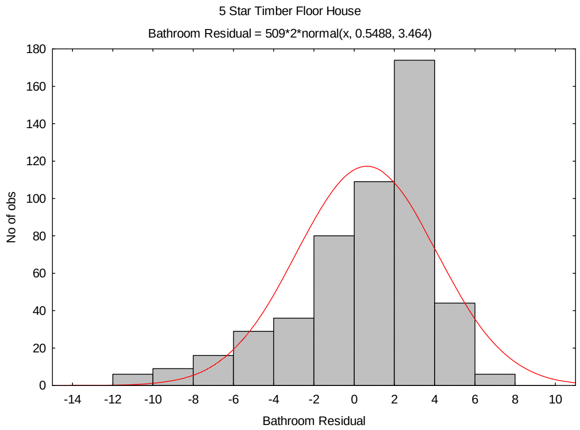

Figure A4.20: Distribution of residuals in the bathroom

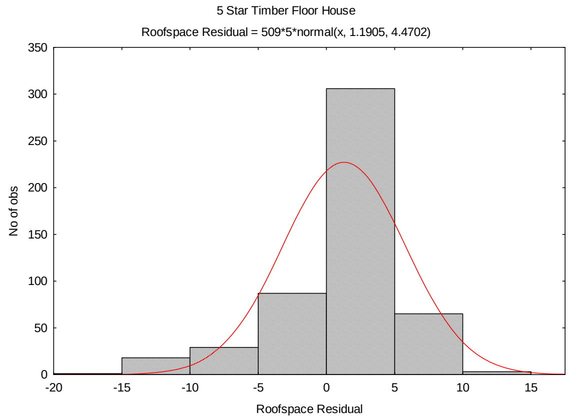

Figure A4.21: Distribution of residuals in the roof space

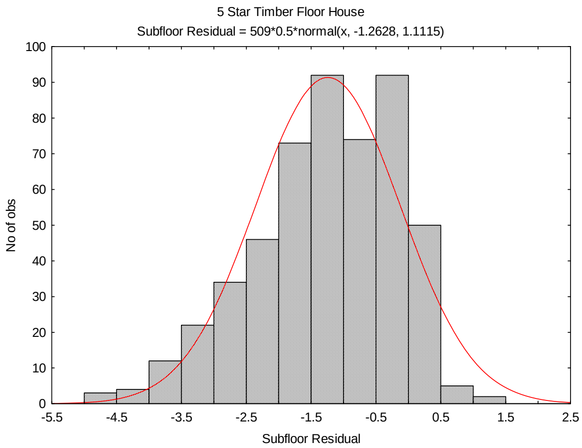

Figure A4.22: Distribution of residuals in the subfloor

Correlation between Zone Residuals and External Air Temperature for the 5-Star Timber Floor House

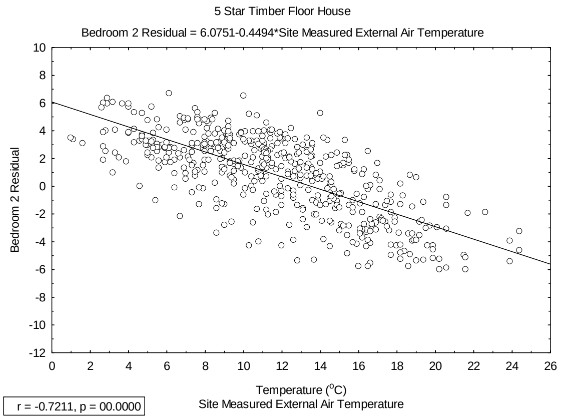

Figure A4.23: Correlation between bedroom 2 residuals and external air temperature

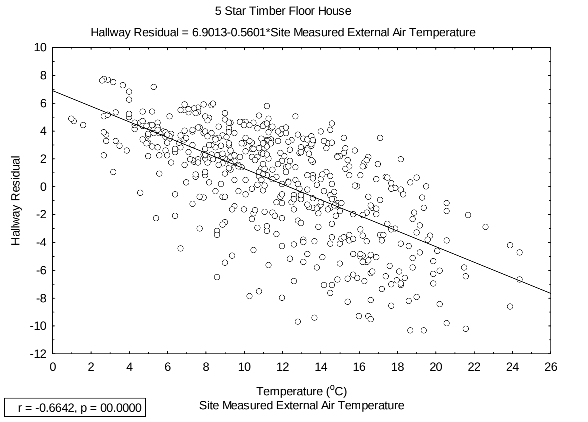

Figure A4.24: Correlation between hallway residuals and external air temperature

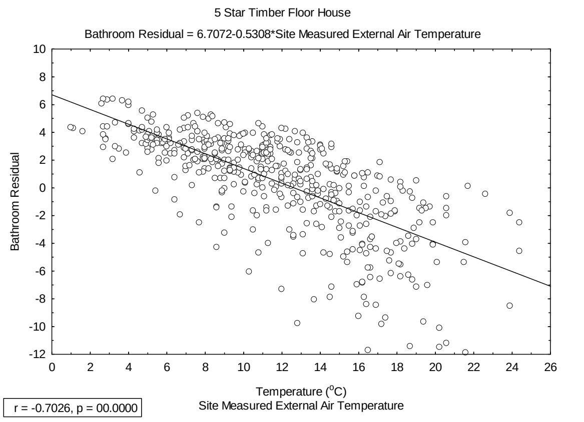

Figure A4.25: Correlation between bathroom residuals and external air temperature

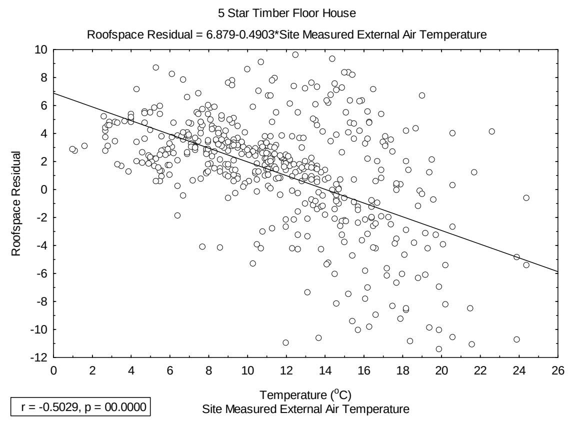

Figure A4.26: Correlation between roof space residuals and external air temperature

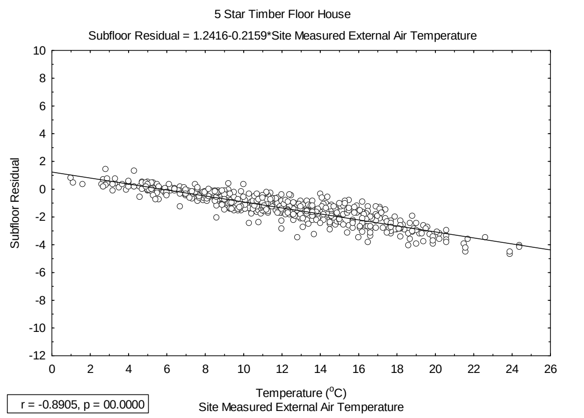

Figure A4.27: Correlation between subfloor residuals and external air temperature

Correlation between Zone Residuals and Global Solar Radiation for the 5-Star Timber Floor House

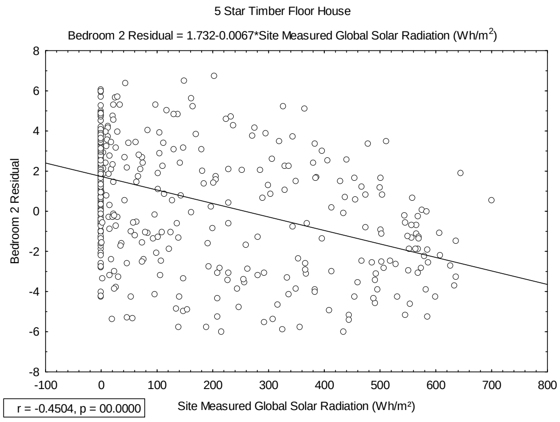

Figure A4.28: Correlation between bedroom 2 residuals and global solar radiation

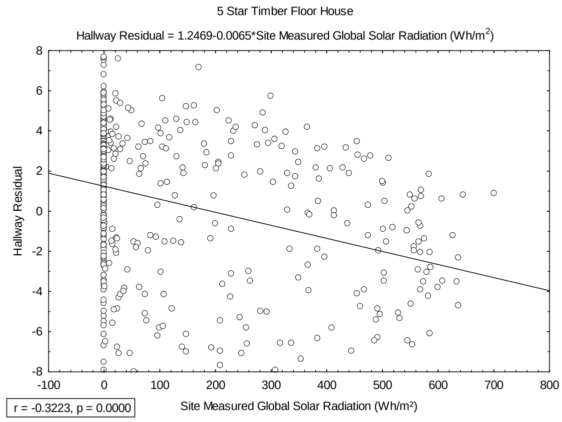

Figure A4.29: Correlation between hallway residuals and global solar radiation

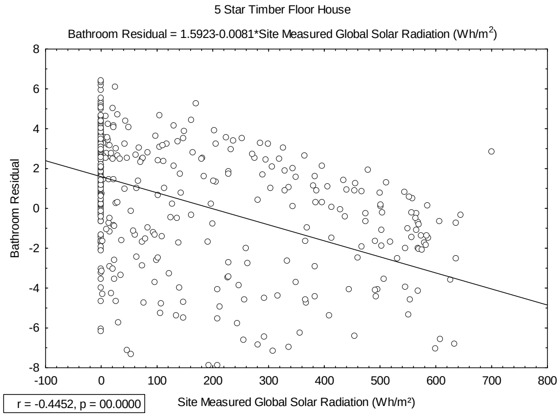

Figure A4.30: Correlation between bathroom residuals and global solar radiation

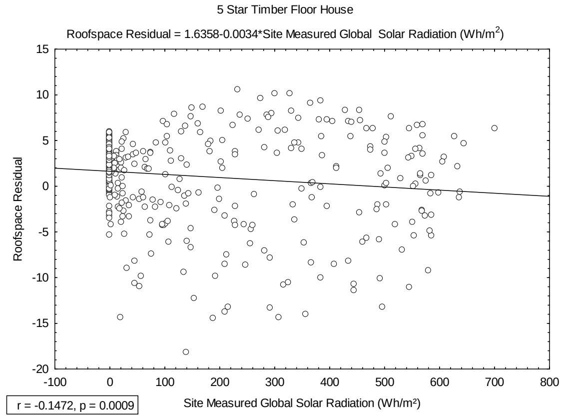

Figure A4.31: Correlation between roof space residuals and global solar radiation

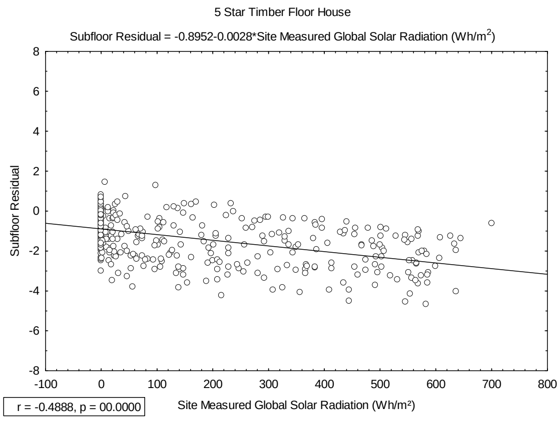

Figure A4.32: Correlation between subfloor residuals and global solar radiation

3) 4-Star Timber Floor House

Correlation between Measured and Simulated Temperatures for the 4-Star Timber Floor House

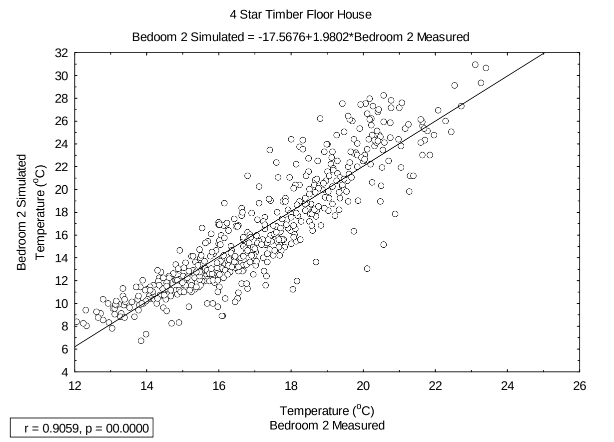

Figure A4.33: Correlation between simulated and measured temperature for bedroom 2

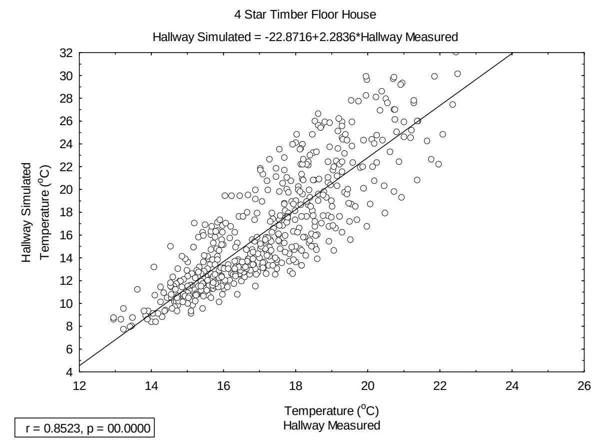

Figure A4.34: Correlation between simulated and measured temperature for the hallway

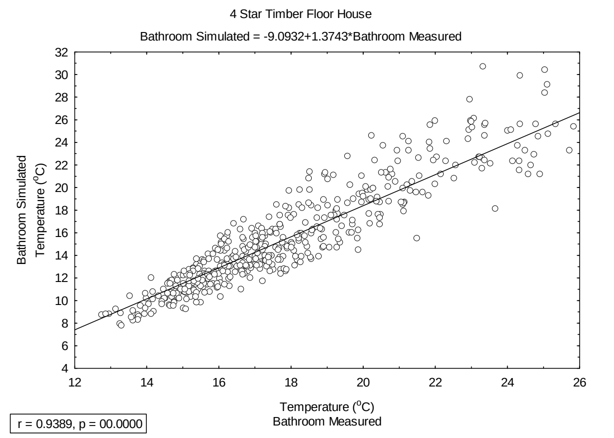

Figure A4.35: Correlation between simulated and measured temperature for the bathroom

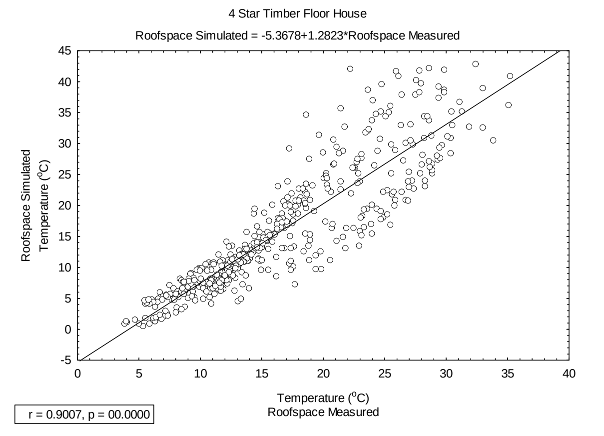

Figure A4.36: Correlation between simulated and measured temperature for the roof space

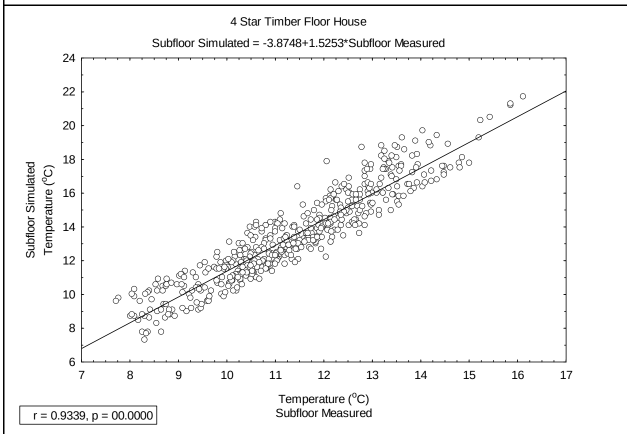

Figure A4.37: Correlation between simulated and measured temperature for the subfloor

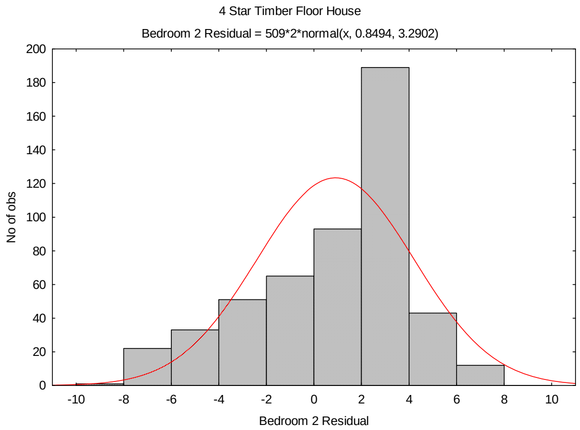

Figure A4.38: Distribution of residuals in bedroom 2

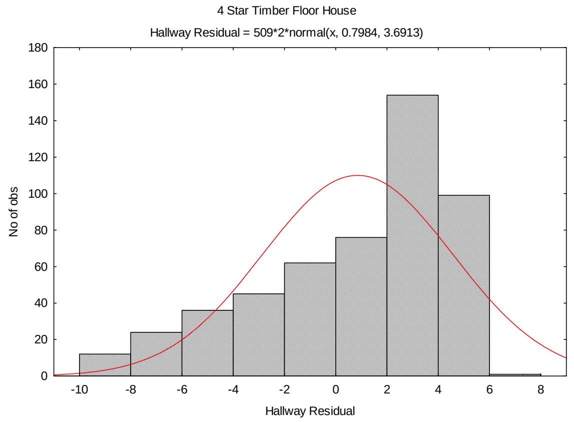

Figure A4.39: Distribution of residuals in the hallway

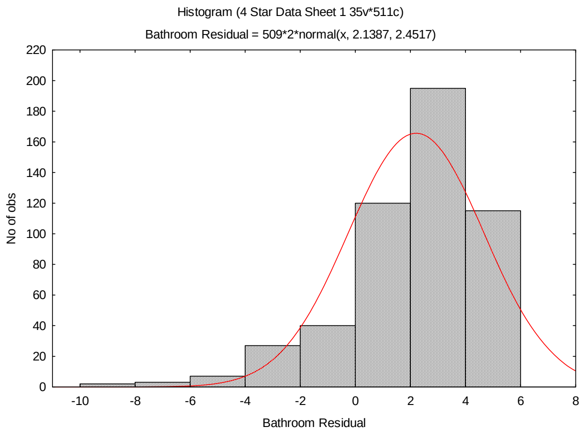

Figure A4.40: Distribution of residuals in the bathroom

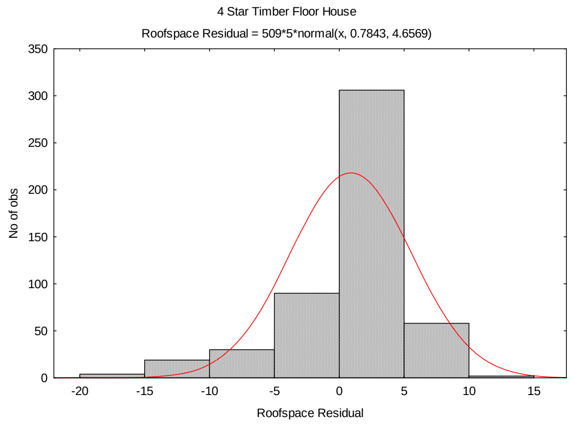

Figure A4.41: Distribution of residuals in the roof space

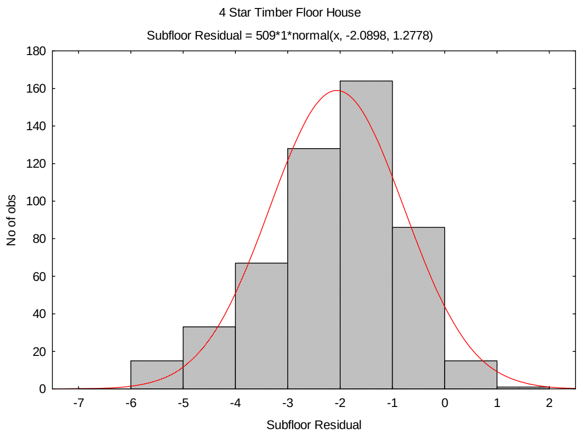

Figure A4.42: Distribution of residuals in the subfloor

Correlation between Zone Residuals and External Air Temperature for the 4-Star Timber Floor House

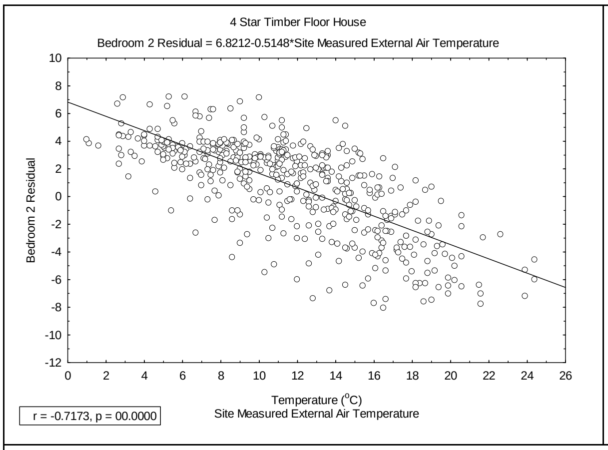

Figure A4.43: Correlation between bedroom 2 residuals and external air temperature

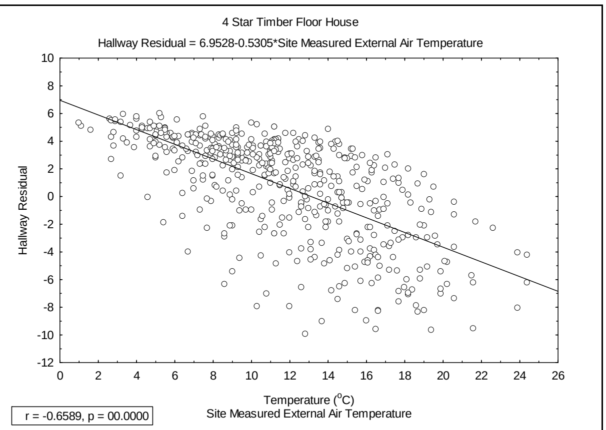

Figure A4.45: Correlation between hallway residuals and external air temperature

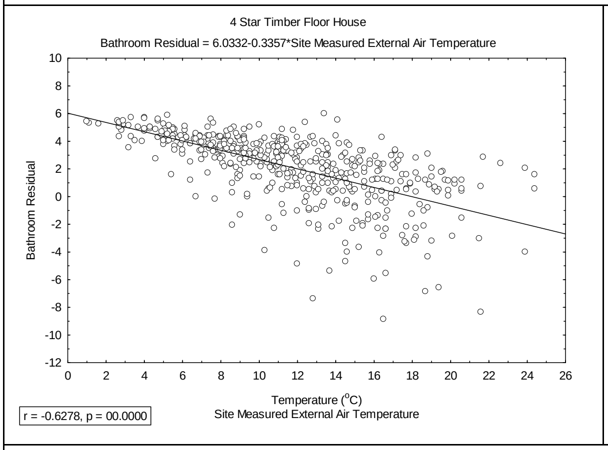

Figure A4.46: Correlation between bathroom residuals and external air temperature

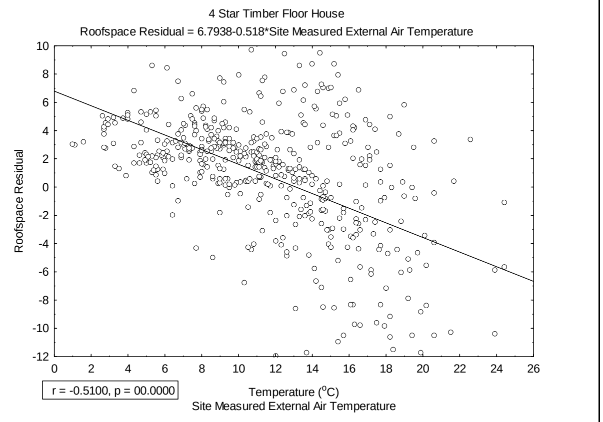

Figure A4.47: Correlation between roof space residuals and external air temperature

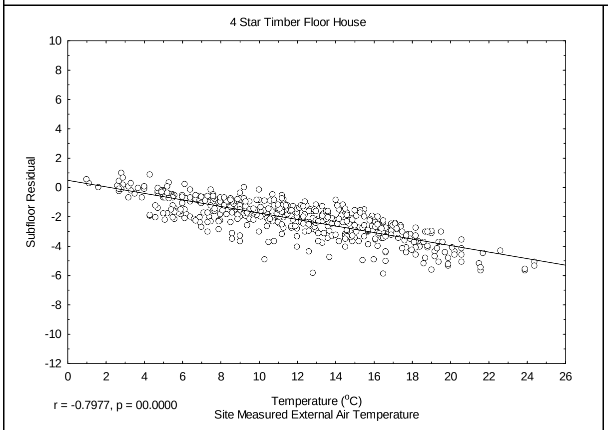

Figure A4.48 Correlation between subfloor residuals and external air temperature

Correlation between Zone Residuals and Global Solar Radiation for the 4-Star Timber Floor House

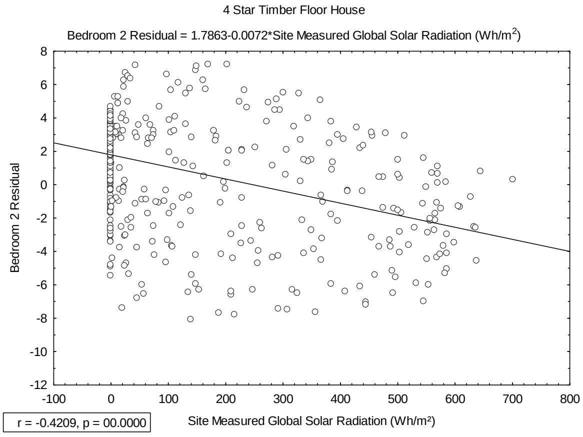

Figure A4.49: Correlation between bedroom 2 residuals and global solar radiation

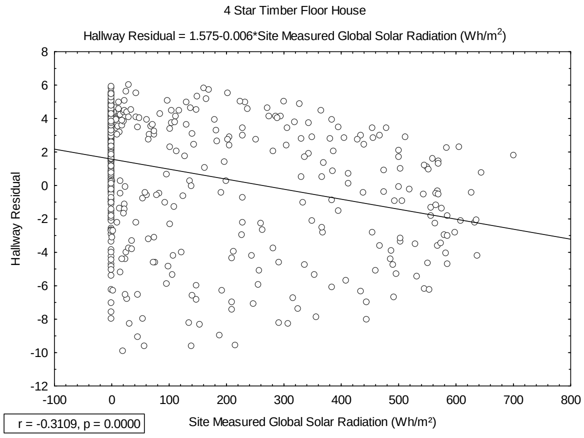

Figure A4.50: Correlation between hallway residuals and global solar radiation

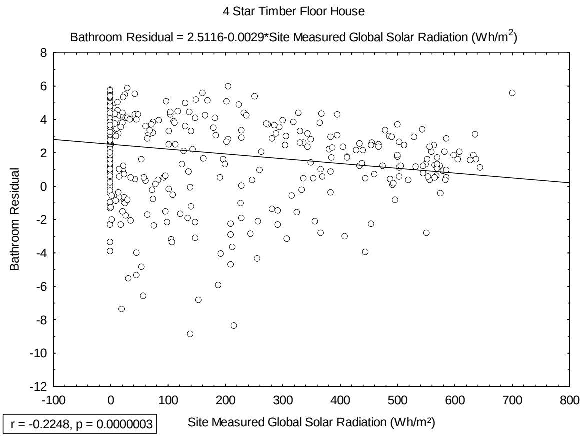

Figure A4.51: Correlation between bathroom residuals and global solar radiation

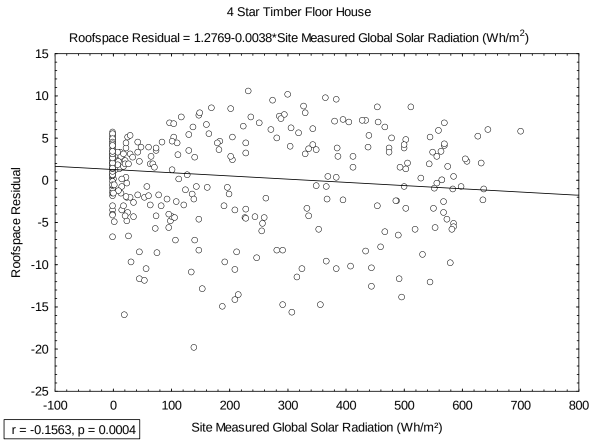

Figure A4.52: Correlation between roof space residuals and global solar radiation

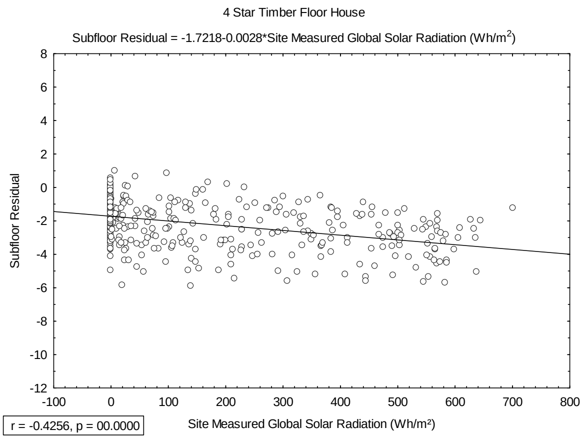

Figure A4.53: Correlation between subfloor residuals and global solar radiation

4) Scatterplot and Fitted Values of Simulated Temperatures and Measured Temperatures for the Hallway, Roof Space and Subfloor for all Test Houses

Hallway Slab Floor House

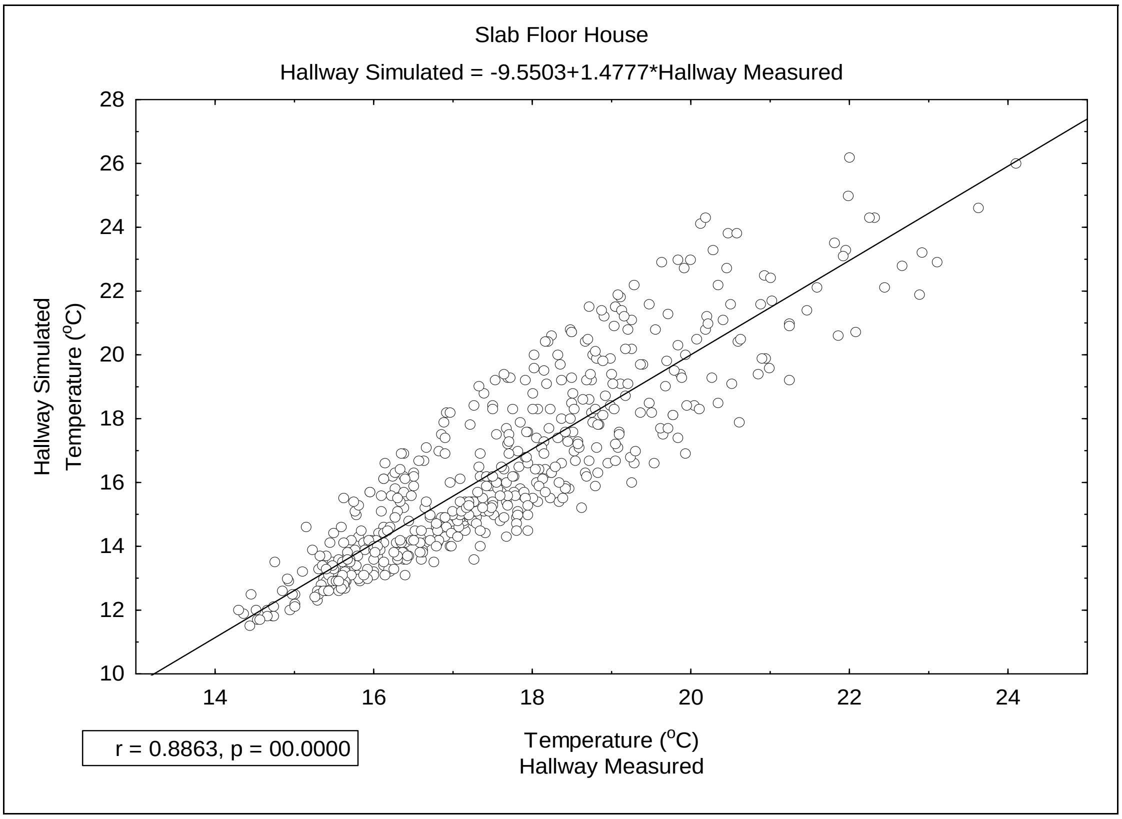

Figure A4.54: Scatterplot of simulated versus measured temperatures in the hallway for the slab floor house

Table A4.1: Fitted values of simulated temperature at various measured temperatures for the hallway of the slab floor house

Measured Temperature (ºC)	Simulated Temperature (ºC)	Residual Temperature (ºC) *
12	8.18	+3.82
16	14.09	+1.91
18	17.05	+0.95
20	20.00	0
22	22.96	-0.96
24	25.91	-1.91

Hallway 5-Star Timber Floor House

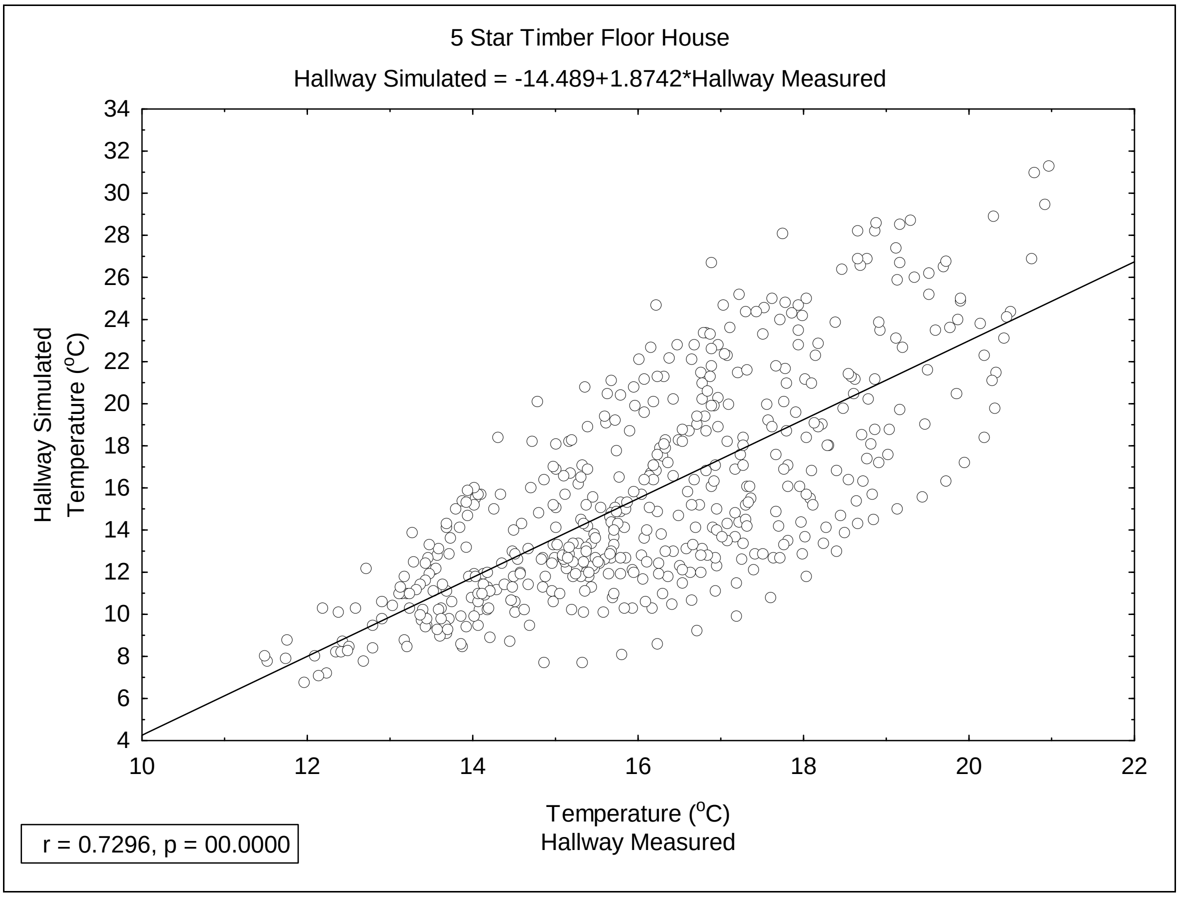

Figure A4.55: Scatterplot of simulated versus measured temperatures in the hallway of the 5-star timber floor house

Table A4.2: Fitted values of simulated temperature at various measured temperatures for the hallway of the 5-star timber floor house

Measured Temperature (ºC)	Simulated Temperature (ºC)	Residual Temperature (ºC) *
12	8.00	+4.00
16	15.50	+0.50
18	19.25	-1.25
20	22.99	-2.99
22	26.74	-4.74
24	30.49	-6.49

Hallway 4-Star Timber Floor House

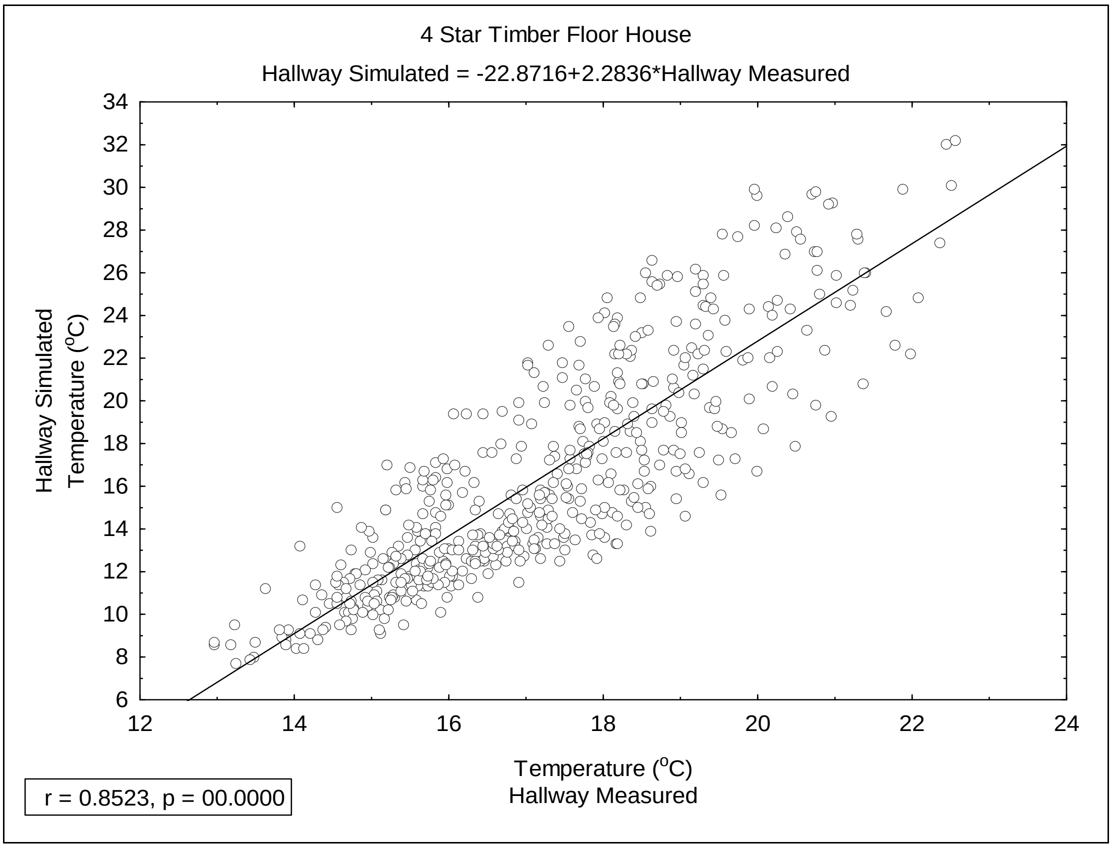

Figure A5.56: Scatterplot of simulated versus measured temperatures in the hallway of the 4-star timber floor house

Table A4.3: Fitted values of simulated temperature at various measured temperatures for the hallway of the 4-star timber floor house

Measured Temperature (ºC)	Simulated Temperature (ºC)	Residual Temperature (ºC) *
12	4.53	+7.47
16	13.67	+2.33
18	18.23	-0.23
20	22.80	-2.80
22	27.37	-5.37
24	31.93	-7.93

Roof Space Slab Floor House

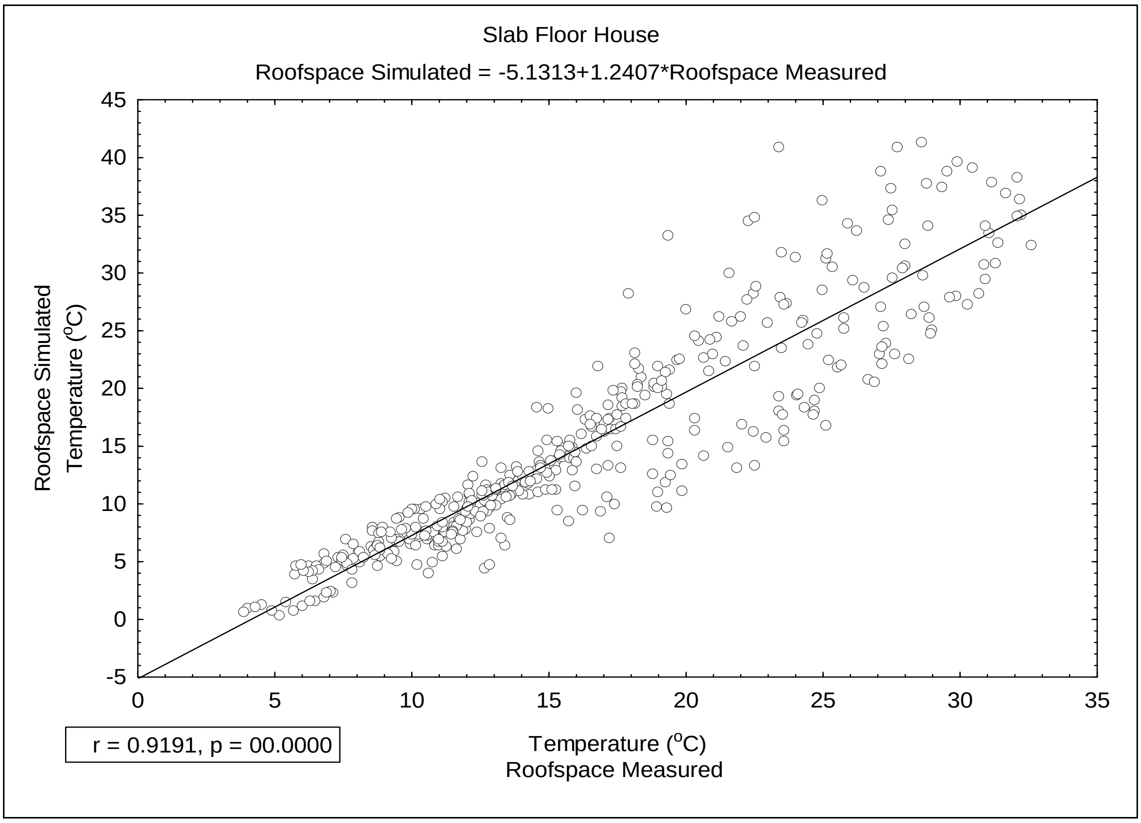

Figure A4.57: Scatterplot of simulated versus measured temperatures in the roof space of the slab floor house

Table A4.4: Fitted values of simulated temperature at various measured temperatures for the roof space of the slab floor house

Measured Temperature (ºC)	Simulated Temperature (ºC)	Residual Temperature (ºC) *
;		
6	2.31	+3.69
10	7.27	+2.73
14	12.23	+1.77
18	17.20	+0.80
22	22.16	-0.16
26	27.12	-1.12
30	32.09	-2.09

Roof Space 5-Star Timber Floor House

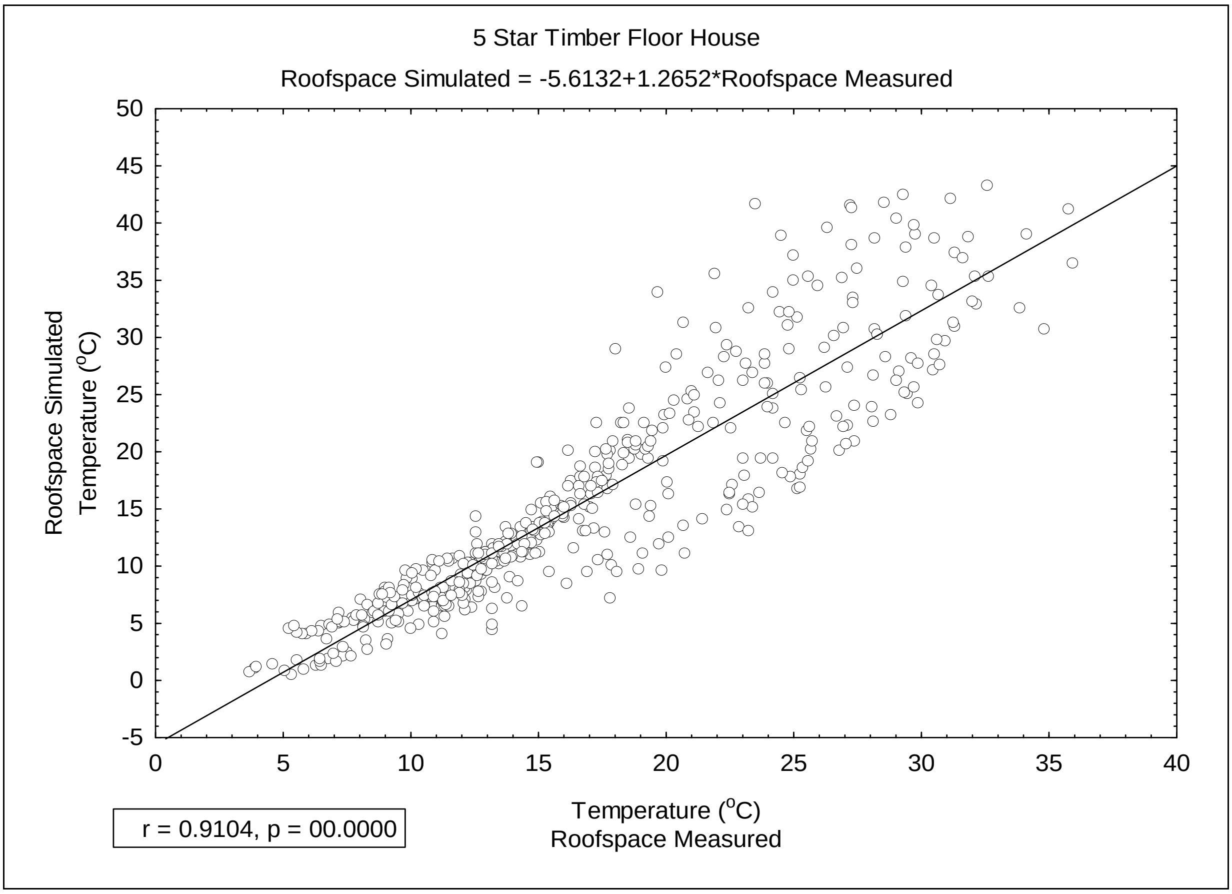

Figure A4.58: Scatterplot of simulated versus measured temperatures in the roof space for the 5-star timber floor house

Table A4.5: Fitted values of simulated temperature at various measured temperatures for the roof space of the 5-star timber floor house

Measured Temperature (ºC)	Simulated Temperature (ºC)	Residual Temperature (ºC) *
6	1.98	+4.02
10	7.04	+2.96
14	12.09	+1.91
18	17.16	+0.84
22	22.22	-0.22
26	27.28	-1.28
30	32.34	-2.34

Roof Space 4-Star Timber Floor House

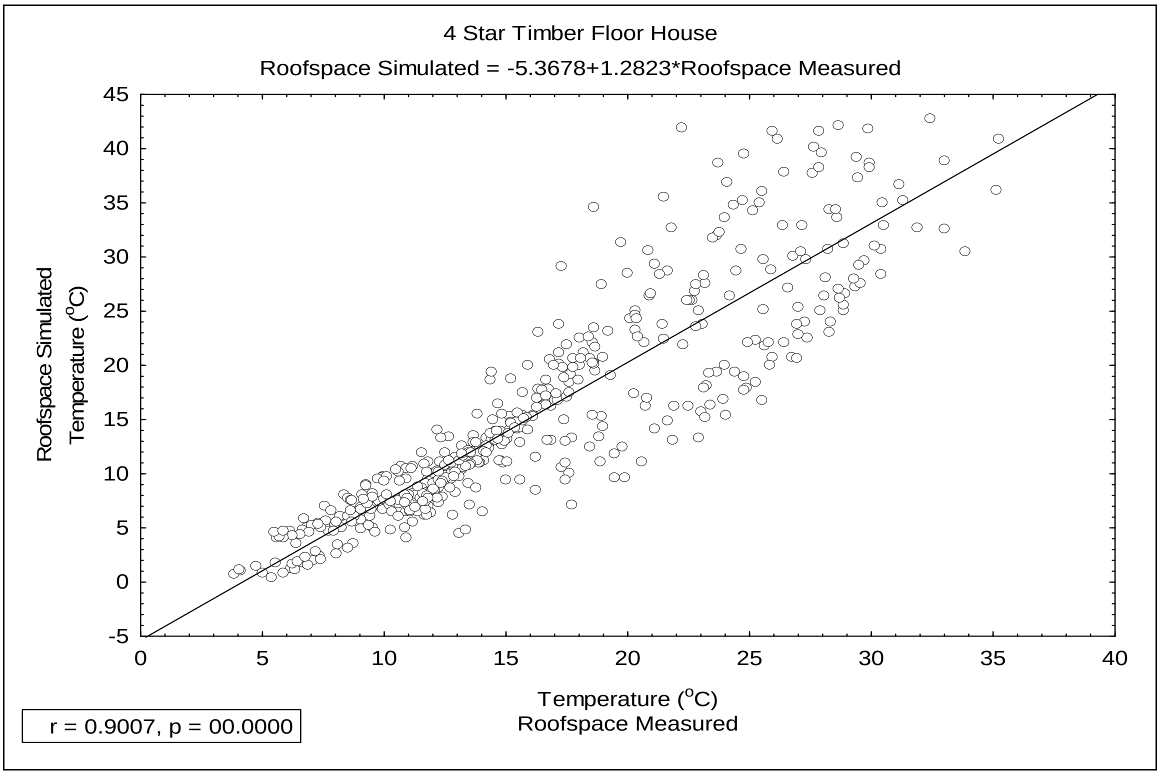

Figure A4.59: Scatterplot of simulated versus measured temperatures in the roof space for the 4-star timber floor house

Table A4.6: Fitted values of simulated temperature at various measured temperatures for the roof space of the 4-star timber floor house

Measured Temperature (ºC)	Simulated Temperature (ºC)	Residual Temperature (ºC) *
6	2.32	+3.68
10	7.45	+2.55
14	12.58	+1.42
18	17.71	+0.29
22	22.84	-0.84
26	27.97	-1.97
30	33.10	-3.10

Subfloor 5-Star Timber Floor House

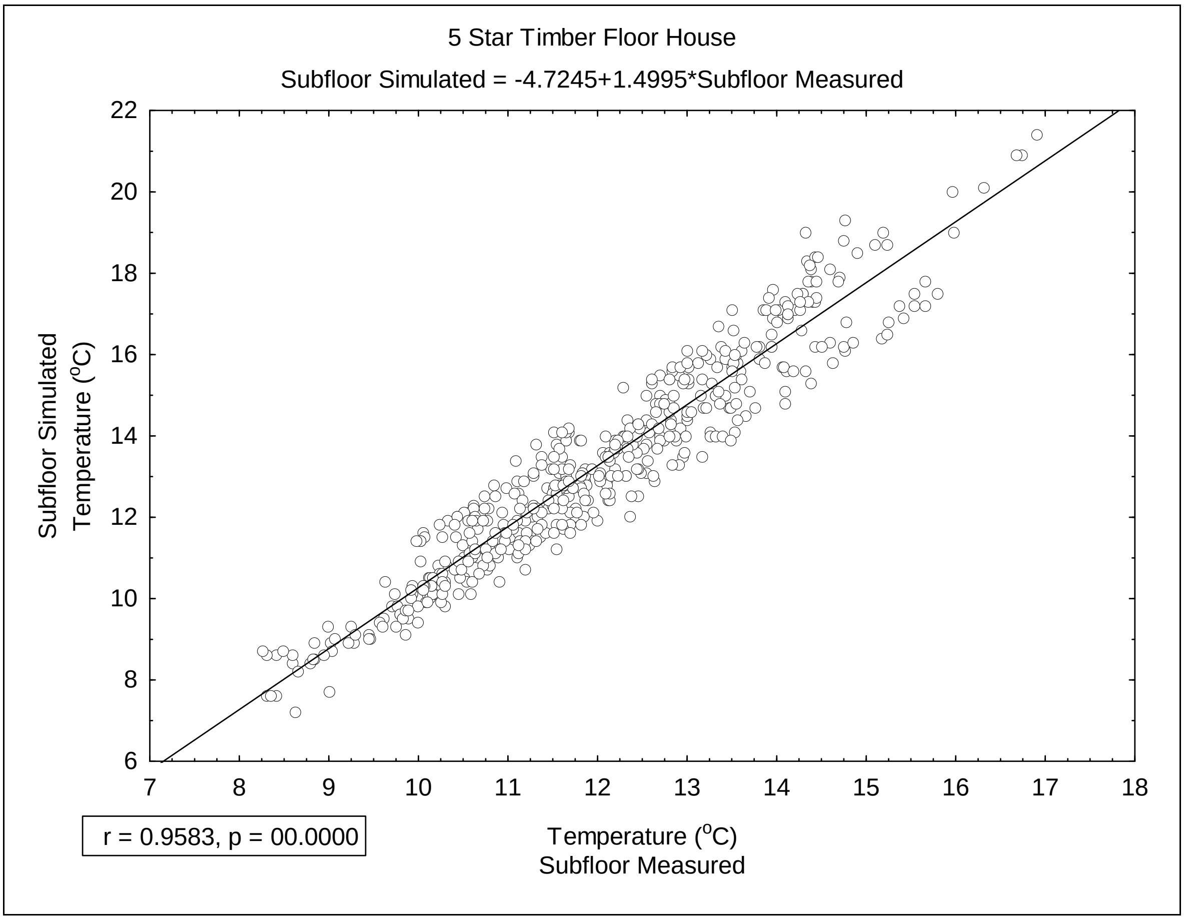

Figure A4.60: Scatterplot of simulated versus measured temperatures for the subfloor in the 5-star timber floor house

Table A4.7: Fitted values of simulated temperature at various measured temperatures in the subfloor of the 5-star timber floor house

Measured Temperature (ºC)	Simulated Temperature (ºC)	Residual Temperature (ºC) *
8	7.27	+0.73
10	10.27	-0.27
12	13.27	-1.27
14	16.26	-2.26
16	19.26	-3.26
18	22.27	-4.27

Subfloor 4-Star Timber Floor House

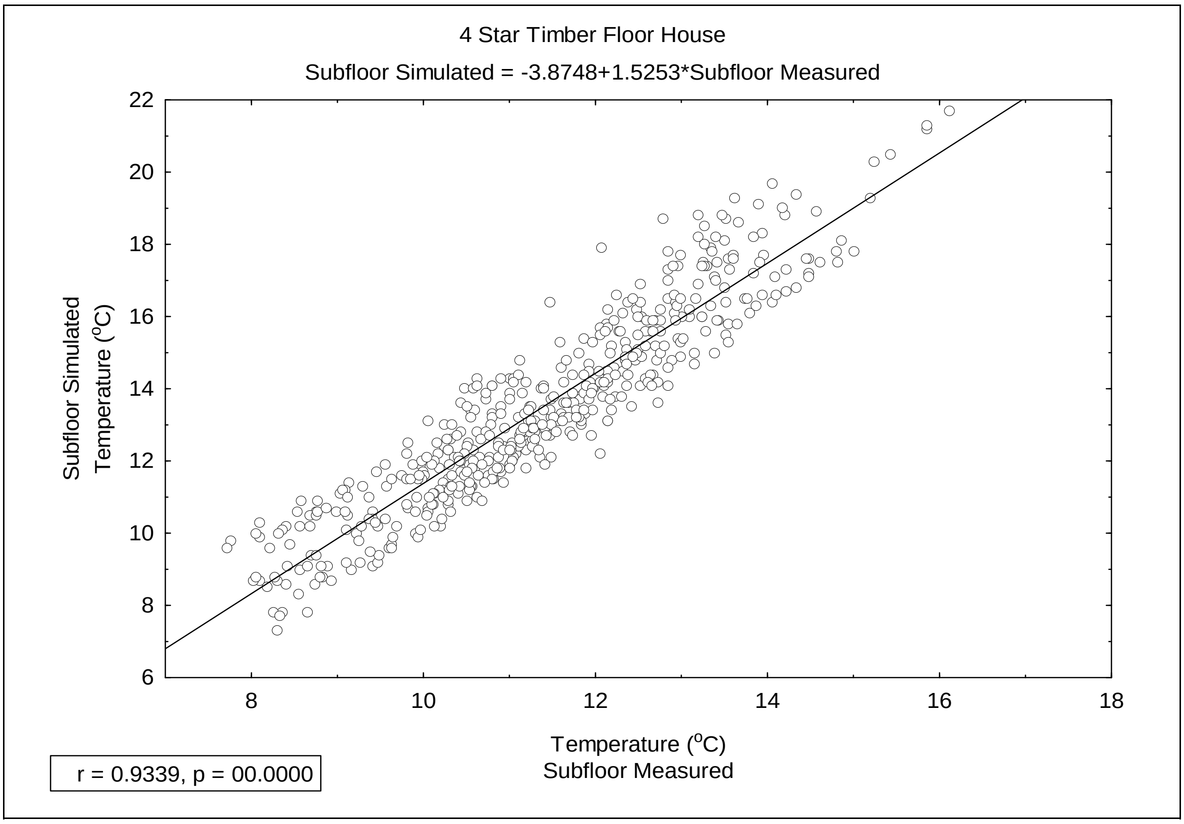

Figure A4.61: Scatterplot of simulated versus measured temperatures for the subfloor in the 4-star timber floor house

Table A4.8: Fitted values of simulated temperature at various measured temperatures in the subfloor of the 4-star timber floor house

Measured Temperature (ºC)	Simulated Temperature (ºC)	Residual Temperature (ºC) *
8	8.33	-0.33
10	11.38	-1.38
12	14.43	-2.43
14	17.47	-3.47
16	20.53	-4.53
18	23.58	-5.58

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